

DETERMINING WATER INFILTRATION
ROUTES FROM STRUCTURES LOCATED
ABOVE CARLSBAD CAVERN,
CARLSBAD CAVERNS NATIONAL PARK,
CARLSBAD, NEW MEXICO


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GROUND WATER STUDIES REPORTS

DETERMINING WATER INFILTRATION ROUTES FROM STRUCTURES LOCATED ABOVE CARLSBAD CAVERN, CARLSBAD CAVERNS NATIONAL PARK, CARLSBAD, NEW MEXICO

by

Paul K.M. van der Heijde, Director
Internat. Ground Water Modeling Center

Kenneth E. Kolm, Associate Professor
Div. of Environmental Sciences and Engineering

Helen Dawson, Assistant Professor
Div. Of Environmental Sciences and Engineering

Mark Brooke, Graduate Student
Dep. of Geology and Geological Engineering

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INTERNATIONAL GROUND WATER MODELING CENTER

Colorado School of Mines
Golden, CO 80401, USA

SUMMARY

Carlsbad Caverns National Park (CCNP), located in the southeastern corner of New Mexico, contains numerous caves that have formed in the underlying fractured limestones, including a visitors accessible cave system, called Carlsbad Cavern. To support and manage the increasing number of visitors, the National Park Service has created over the years an extensive infrastructure with facilities both above ground and underground. The impact on the caves of the resulting anthropogenic activity in and around these facilities has become a concern to Park management. The focus of this project was to determine the potential impacts of man-made structures and human activities at the land surface on Carlsbad Cavern. Specifically, the study aimed at determining the cave areas most vulnerable to contamination from the land surface through hydrologic pathways, and if impacts from these anthropogenic influences on the hydrology and water quality of the cave system are currently present.

The approach taken in this study has been based on developing a thorough understanding of the hydrologic system, and the use of a qualitative classification system tailored to the specific local circumstances. The development of a conceptual model of the hydrologic system was conducted using a modified version of the conceptualization and characterization approach of Kolm (1993) and Kolm et al. (1996). This work was augmented by a series of sampling events to determine general and anthropogenic chemical characteristics of percolating water. To facilitate the vulnerability assessment, so-called "hydrologic system domains" have been defined, based on the developed hydrologic system model. These domains are zones dominated by specific hydrologic mechanisms and hydrogeologic controls resulting in a characteristic set of infiltration pathways. The collected chemical data were used, among others, to corroborate these infiltration pathways.

A number of factors present at the study site contribute to a relative high vulnerability of the caves: 1) the absence of a significant, continuous soil zone in most of the study area; 2) the presence of localized but highly permeable fracture zones; and 3) the presence of well developed karst in most of the relevant profile. Factors that have a moderating influence on cave vulnerability include the arid climate, and the presence in part of the

study area of the rather continuous Yates Siltstone and a (shallow) subcutaneous zone. The arid climate is responsible for the small amounts of water that infiltrates in the cavern, providing only a minor driving force for movement of contaminants. Only intense storms may cause a major downward flow. Furthermore, intense homogenization of water quality takes place in most of the study area due to the presence of the subcutaneous zone, the Yates Siltstone, and other-low permeability barriers to rapid infiltration. Over time, this results in a reduction of the concentrations that eventually move downwards beneath these barrier layers. Exceptions are the "gap" in the Yates Siltstone in the Main Corridor, the macrofractures in the area of Chocolate High, New Mexico Room, Scenic Rooms, and Big Room, and the southern edge of the Yates Siltstone.

A major concern is that most of the Park facilities at the surface are situated directly above important cave resources. From the study it is concluded that the most threatened areas in Carlsbad Cavern are: 1) Quintessential Right, 2) Left Hand Tunnel, 3) New Section, 4) the Main Corridor between Devil's Spring and Iceberg Rock, and 5) locations in Chocolate High, the New Mexico Room, the Scenic Rooms, and the Big Room area.

Although Carlsbad Cavern is highly vulnerable for contamination from the surface, currently, there are few indications that massive contamination is occurring. Some smaller incidences have been detected, primarily related to chronic, low-level releases from sewer lines and parking lot runoff. However, it is very conceivable that in the future a major contamination incident may take place if no preventive measures are taken.

After a contaminant has entered the subsurface, little can be done to remove it until it arrives, often many years later, in an exposed cave. There, some measures can be taken to capture and remove the contaminant and to reduce its potential effect on humans and cave ecosystems. Even then, most contamination incidents will be rather localized or will occur in areas not accessible for visitors, allowing most of the caves to be kept open for the public.

To protect the caves from further contamination from the surface, the chance of a significant release at the surface needs to be reduced through management policies, accident mitigation procedures, and engineering measures.

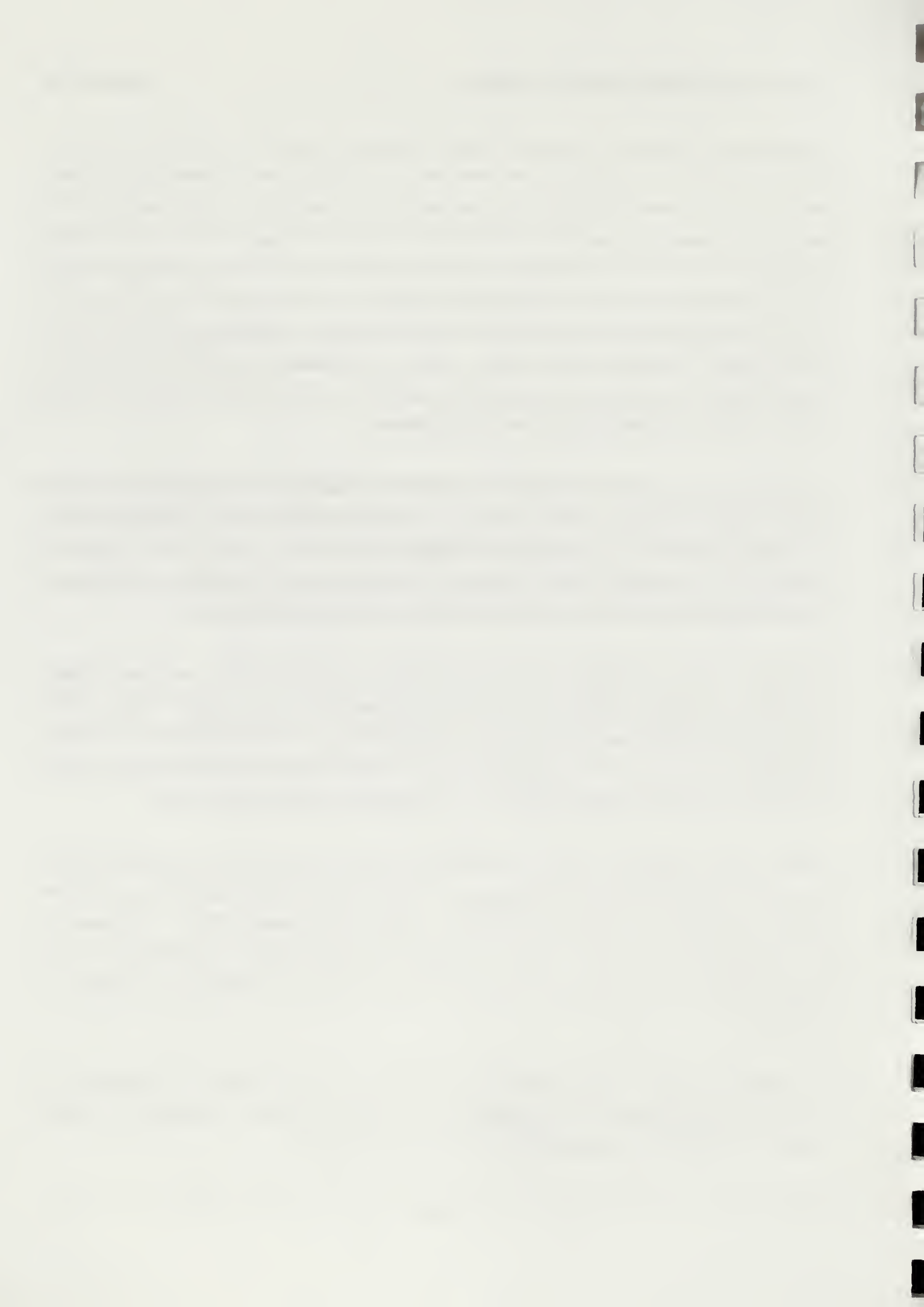


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FOREWORD

This report has been prepared for the Carlsbad Caverns National Park, National Park Service, Carlsbad, New Mexico, as a deliverable under Cooperative Agreement CA 7029-4-0017 with the Colorado School of Mines (CSM). The project has been managed by the International Ground Water Modeling Center (IGWMC), a research and technology transfer center at CSM's Department of Geology and Geological Engineering. The main objective of the study was to provide Park managers with adequate information and data to prevent and abate cave contamination from surface sources.

The project has been carried out under the responsibility of Dr. Kenneth E. Kolm, Associate Professor, Division of Environmental Sciences and Engineering, Principal Investigator, and Mr. Paul K.M. van der Heijde, Director, International Ground Water Modeling Center, Project Manager and Co-Investigator. Dr. Helen Dawson, Assistant Professor, Division of Environmental Sciences and Engineering advised on chemical sampling, field and laboratory analysis, and statistical analysis and interpretation of chemical data. Much of the field work and the data analysis and interpretation was performed by Mr. Mark Brooke, Graduate Student, Geology and Geological Engineering, Colorado School of Mines, who reported his findings in a thesis for Master of Engineering, entitled "Infiltration Pathways at Carlsbad Cavern National Park Determined by Hydrogeologic and Hydrochemical Characterization and Analysis", defended in November 1996. The current report refers extensively to Mr. Brooke's thesis and includes many of the data and findings reported by Mr. Brooke.

The authors recognize the extensive assistance received from Park management and resource specialists at Carlsbad Caverns National Park, without which successful completion of this study would not have been possible. The authors specifically appreciate the assistance received from Cave Specialist Dale Pate, the Contracting Officer's Technical Representative for the project.

Paul K.M. van der Heijde
Kenneth E. Kolm
Golden, Colorado
January 1997.

DETERMINING WATER INFILTRATION ROUTES FROM STRUCTURES LOCATED ABOVE CARLSBAD CAVERN, CARLSBAD CAVERNS NATIONAL PARK

INTRODUCTION

Carlsbad Caverns National Park (CCNP), located in the southeastern corner of New Mexico (Figure 1), contains numerous caves that have formed in the underlying fractured limestones, including a visitors accessible cave system, called Carlsbad Cavern. The existence of the caves was known to local ranchers in the late 19th century, although little was known about the extent of the cave system at that time. In the first decade of the 20th century, the Bat Cave area, a part of the Carlsbad Caverns where hundred of thousands of bats reside, became the focus of guano mining which lasted into the early 1920s. In 1923, the cave system became a National Monument and in 1930 Carlsbad Caverns National Park was established.

To support and manage the increasing number of visitors, the National Park Service has created an extensive infrastructure with facilities both above ground and underground. The impact on the caves from the resulting anthropogenic activity in, and around the Visitor's Center, the parking lots, offices, maintenance facilities and staff quarters, and other areas overlying portions of the Carlsbad Caverns portion of the Park, has become a concern to Park management. The focus of this project was to determine the potential impacts of man-made structures and human activities at the land surface on the Carlsbad Cavern system. Specifically, the study aimed at determining the cave areas most vulnerable to contamination from the land surface through hydrologic pathways, and if impacts on the hydrology and water quality of the cave system from anthropogenic influences, are currently present.

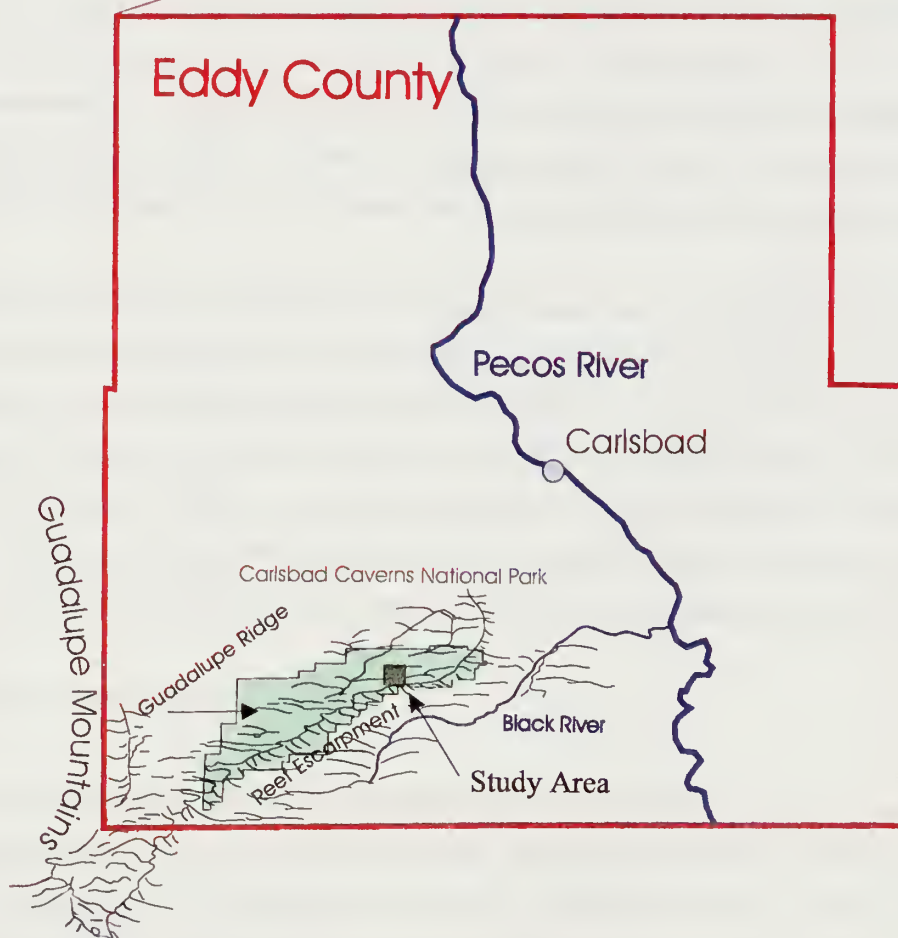
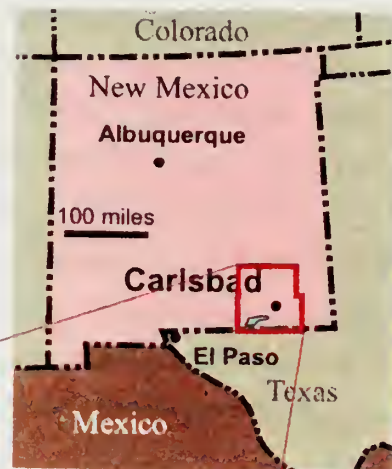


Figure 1. Location of study area (from Brooke, 1996).



General Description

Carlsbad Cavern is part of a larger hydrologic system that includes the Guadalupe Mountains as its regional recharge area and the Pecos River as its regional discharge area (Tallman, 1993) (Figure 1). The caverns lie within the Guadalupe Ridge, a structural system that has been superimposed on the older Permian reef lithology. This ridge has a surface elevation within the CCNP study area ranging from 1220 m (4000 ft) to 1370 m (4500 ft) above MSL (mean sea level), and borders to the south on the Delaware Basin, over 300 m (1000 ft) below, also known as the Gypsum Plain. The boundary between the ridge and the basin is marked by intersected alluvial deposits ranging from about 1160 m (3800 ft) elevation near the ridge to about 975 m (3200 ft) where they phase out into the basin.

The known caves in Carlsbad Cavern are situated between 1370 m (4500 ft) (Natural Entrance) and 1010 m (3300 ft) (Lake of the Clouds). The regional water table is estimated to be situated at about 45 m (150 ft) below the elevation of the Lake of the Clouds (Hill, 1987). There are approximately 53 km (33 miles) of mapped subsurface cavern passages on four main levels and several additional sublevels.

The four main karst levels at Carlsbad Cavern are: the Bat Cave level at 1265 m (4150 ft), the New Section level at 1225 m (4020 ft), the Big Room level at 1115 m (3650 ft), and the Lower Cave level at 1090 m (3575 ft) (Figures 2, 3 and 4). The sublevels include the Lake of the Clouds at 1010 m (3300 ft), and the Guadalupe Room, which descends from the New Section level to a maximum depth of 1130 m (3700 ft). Most of the passages are cavernous, but some sections of the cavern contain narrow passages, due to both lithologic and structural controls on cavern development (Jagnow, 1977).

Cave Vulnerability

As stated above, this study explored the vulnerability of the caves of Carlsbad Cavern to contamination from the land surface. Vulnerability can be defined as the tendency or likelihood for contaminants to reach a specific position in the subsurface after their introduction at some location at or near the surface (NRC, 1993). Vulnerability is not an



Figure 2. Plan and profile views of Carlsbad Cavern (from Brooke, 1996).



Figure 3. Carlsbad Cavern room locations (from Brooke, 1996).

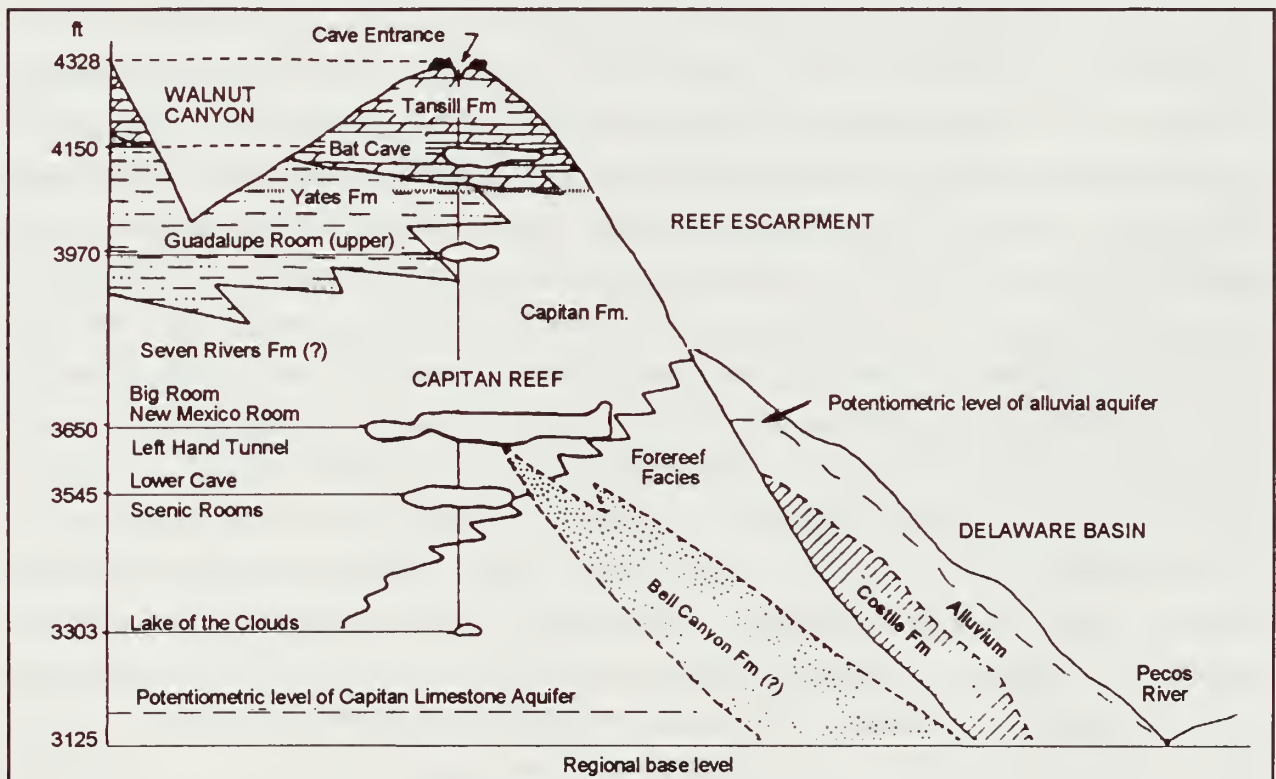


Figure 4. Schematic (geo-)stratigraphic profile of Carlsbad Cavern area (from Hill, 1987).

absolute property, but a relative indication of where contamination is likely to occur. In recent years, the concept of vulnerability has received broad attention in relation to ground-water protection, both from the research community as from the public policy and enforcement side (van Duijvenbooden and van Waegeningh, 1987; EPA, 1991; Pettyjohn et al., 1991; NRC, 1993; Vrba and Zaporozec, 1994). Much less attention has been given to assess the vulnerability of the unsaturated zone, the dominant zone present in the Carlsbad Cavern hydrogeologic system, or directly to the vulnerability of caves.

The potential of contaminants to leach into the caves and the underlying water table depends on many factors, including the composition, structure, texture and permeability of soils and rock, the topography of the local terrain (specifically slope), the amount of precipitation available for infiltration in the subsurface and subsequent percolation through the unsaturated zone, and type and control of land use. To assess the caves' vulnerability, the study addressed four major objectives: (1) identify and characterize potential contaminant sources; (2) determine the presence and nature of contaminant pathways from these potential contaminant sources at or near the land surface to the caverns; (3) determine present impacts from these anthropogenic sources on the hydrology and water quality of the cave system, and (4) evaluate the likelihood of future contamination of the cave system. It should be noted that uncertainty is inherent in all vulnerability assessments (NRC, 1993). Furthermore, it may be relatively straightforward to determine areas that are rather vulnerable for contamination from the surface, e.g., in the presence of mature karst or alluvial sand and gravel deposits. However, it is typically much more difficult to determine that an area has a low vulnerability. The integrity of low permeable rock may be compromised by the existence of preferential pathways from faulting and fracturing, or because of the differential rock properties within the formations at a scale not detected by field exploration.

Assessment Method

The major methods developed for predicting ground-water vulnerability are (NRC, 1993): 1) overlay and index methods that combine specific physical characteristics that affect vulnerability; 2) process-based methods consisting of mathematical models that approximate the behavior of pollutants in the subsurface; and 3) statistical methods that

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draw associations with areas where contamination is known to have occurred. Due to the uniqueness of the Carlsbad Cavern system, the third type of analysis could not be applied: there are simply no comparable hydrologic systems that have been studied in enough detail. The complexity of the hydrogeologic system, the lack of quantifying information, and the inability to conduct intrusive data gathering at the site prevented the study team from performing model-based analysis. Therefore, the selected study approach was based on extensive and detailed mapping of relevant physical entities, analyzing their impact through GIS- and CAD-based overlay techniques, and developing a qualitative classification system. Due to the uniqueness of the study area, the study has not employed an index system, such as described in the DRASTIC method (Aller et al., 1987), but rather indicated the level of vulnerability using qualitative terms (extreme, high, moderate, low), and in terms of typical ranges of travel times or residence times. Residence times are indicative for the time it may take a contaminant to move from its source to a point of human or ecosystem exposure in the caves. They have been estimated by combining published and newly obtained information on intrinsic and secondary permeability with the results of hydrologic evaluation of likely pathways, isotope studies, and studies regarding the residence times in comparable hydrologic systems. This work was augmented by a series of sampling events to determine general and anthropogenic chemical characteristics of percolating water.

The mapping of physiographical elements and their combination in the development of a conceptual model of the hydrologic system was conducted using a modified version of the conceptualization and characterization approach of Kolm (1993) and Kolm et al. (1996). This involved the following phases (Figure 5): 1) data gathering and preliminary conceptualization; 2) surface, geomorphologic, geologic and chemical characterization; 3) hydrogeologic characterization; 4) hydrologic system analysis; and 5) vulnerability assessment. The result of data collection and interpretation, as well as many of the maps and figures prepared for the first four phases of this study, have been reported in Brooke (1996) and are summarized in this report; a description of phase 5 is also included.

The interpretation of the physiographic data is illustrated in the form of maps and cross-sections. To facilitate the vulnerability assessment, so-called "hydrologic system domains" have been defined, based on the results of the hydrogeologic characterization (i.e.,

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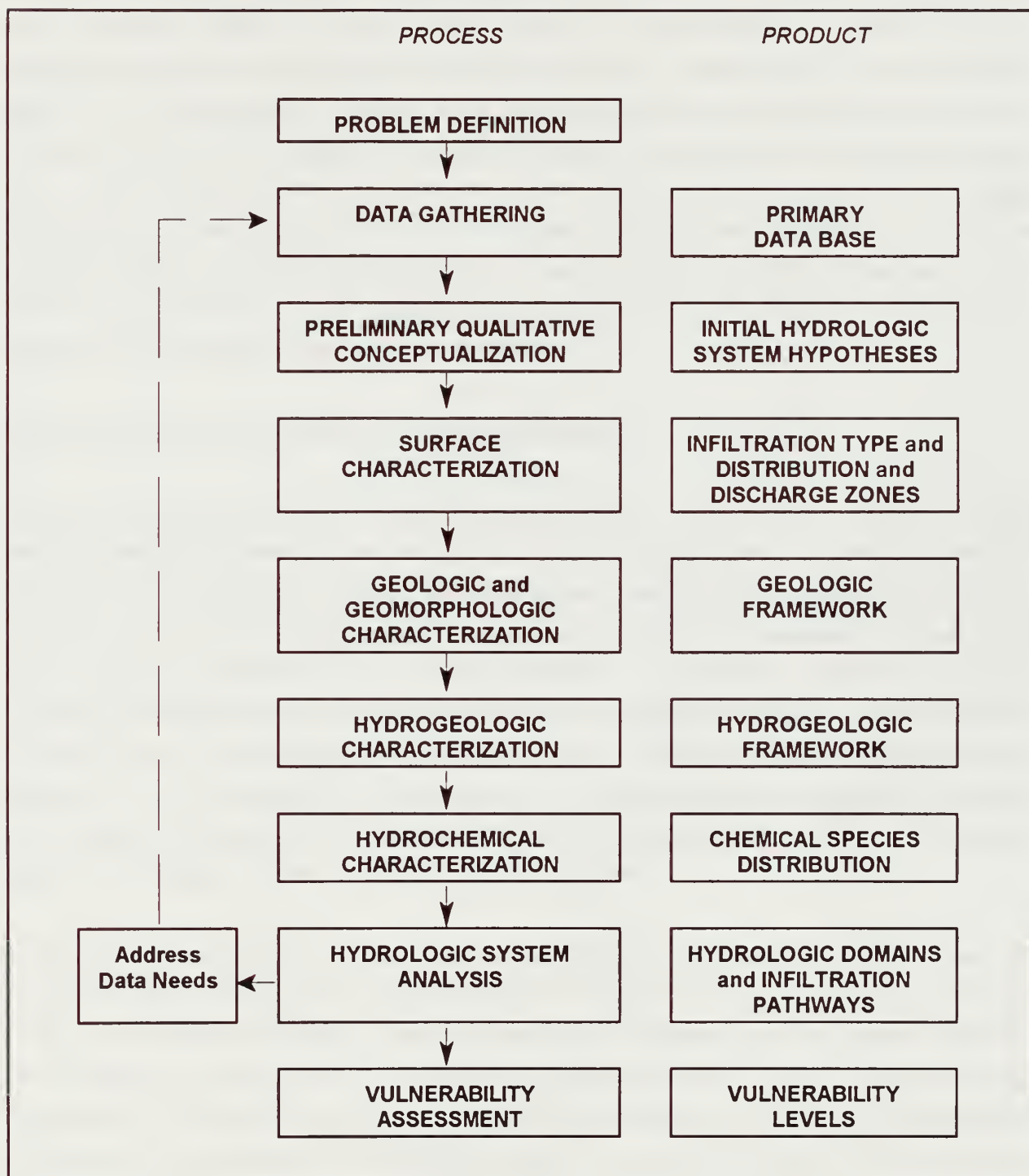


Figure 5. Flow diagram of hydrologic system analysis for Carlsbad Cavern (modified from Kolm et al., 1996).

overlays of maps of relevant physical properties), and the developed hydrologic system model (Brooke, 1996). These domains are zones dominated by specific hydrologic mechanisms and hydrogeologic controls resulting in a characteristic set of infiltration pathways. Overlaying the hydrologic system domains with a map of the potential sources of contamination at the surface provides the distribution of vulnerability levels at the study site. The collected chemical data were used, among others, to corroborate these infiltration pathways. Due to the lack of actual data regarding contaminants and the physical system, this study has focused on the determination of *intrinsic* vulnerability only. *Specific* vulnerability, i.e., the vulnerability of the caves for particular contaminants or group of contaminants, has not been addressed.

Concepts Regarding the Movement of Contaminants

All naturally occurring water contains dissolved solids. The type and amount of these solutes change as water moves through soil and rock as the result of various chemical, physical and biological processes. Moreover, natural water typically includes bacteria and viruses, some of which may be detrimental to human health. Changes of natural water quality may occur as the results of human activity. Contamination occurs when these anthropogenic activities cause such deterioration of the quality of natural water that its use is restricted, or that damage to ecosystems is likely. Although natural processes may reduce the seriousness of the contamination, many contaminants remain essentially unchanged after entering the subsurface (Vrba and Zaporozec, 1994). Thus their detrimental effects can persist for a long period of time.

Transport of contaminants takes place in dissolved form by percolation of the solvent (mostly water), or directly as a contaminating non-aqueous phase liquid (NAPL) through pores and channels in the rock. They may be subject to sorption onto the mineral surfaces of the soil or rock matrix, (bio-)chemical degradation and other contaminant fate processes. In this study, such chemical fate processes are not taken into consideration, resulting in a conservative (worst-case) analysis. Very little is known about chemical interaction of contaminants and carbonate rock systems which characterize Carlsbad Cavern.

Infiltration from rain and melting snow is the major natural driving force for contaminant movement in the study area, locally augmented by water from washing vehicles, cleaning paved surfaces, (lawn) irrigation, and incidental water releases. The infiltration process (and the introduction of contaminants in the subsurface) is highly variable in time, due to variations in precipitation during a typical year, as well as variations in precipitation patterns over longer periods of time. Furthermore, infiltration rates are highly dependent on local factors such as terrain slope, and soil type and condition. Where present, paved surfaces concentrate and redistribute runoff and subsequent infiltration.

Solutes that do not react among themselves or with the surrounding rock are carried with the average rate of flow of water in the subsurface (so-called "advective transport" or "advection"). In addition, they may be subject to hydrodynamic dispersion resulting in mixing of the contaminated water with neighboring clean water. Cave vulnerability, as assessed in this study, is based on the analysis of advective transport in the various geological strata present between the land surface and the various cave elevations. This means that if a pathway exists between a particular location at the land surface and a particular cave, and a contaminating substance is introduced at that surface location, it will eventually reach the cave.

Previous Work

Most of the previously reported research at Carlsbad Cavern pertains to the geology and geochemistry of the caves and the surrounding area. Few studies focused on the current hydrology of the cave system. Brooke (1996) provides an overview of the main published contributions to the understanding of the geology and hydrology of the study area.

Past hydrological studies focused on the regional hydrological system, primarily related to ground-water issues (Motts, 1957, 1968; Bjorklund and Motts, 1959; Hiss, 1974, 1975, 1976, 1980; and Tallman, 1993). Boyer (1964), Thrailkill (1965), and Hill (1987) studied the major-ion water chemistry of drips and pools in Carlsbad Cavern. Ingraham et al. (1990), Chapman et al. (1992), and Lambert (in review) reported on the results of isotope studies of the drip and pools.

Williams (1983) studied the role of the subcutaneous zone in karst hydrology and compared its presence in various karst system including Carlsbad Cavern. He argued, that due to erosion and dissolution, the upper karst layers located below the soil horizon provide ample storage for infiltrating water. As the rock becomes more competent with depth, it acts as a barrier to vertical flow. Thus, recharge waves are damped and the quality of infiltrating water homogenized. Furthermore, the subcutaneous zone act as a collection drain, focusing infiltrating water towards master joints and solution channels. He used lag times between precipitation events and increased percolation rates and pool levels in Carlsbad Cavern as a verification example of this mechanism. Ingraham et al. (1990) discussed the water balance of cave pools and included assessments of the contribution of percolating water and downwards seepage from the pools. Chapman et al. (1992) determined that (water) travel times between the land surface and the main cave rooms typically are on the order of decades. Both studies were based on the use of stable isotopes in drips and pools. Lambert (in review) used isotopes to determine recharge rates at Carlsbad Cavern. His study focused on the characteristic precipitation events responsible for the major part of ground-water recharge in the area. He determined that only precipitation events lasting several days correlated to the percolation signal.

1. The first part of the document discusses the importance of maintaining accurate records of all transactions and activities. It emphasizes the need for transparency and accountability in financial reporting.

2. The second part of the document outlines the various methods and techniques used to collect and analyze data. It includes a detailed description of the experimental procedures and the statistical analysis performed.

3. The third part of the document presents the results of the study. It includes a series of tables and graphs that illustrate the findings of the research. The data shows a clear trend of increasing activity over time.

4. The fourth part of the document discusses the implications of the findings. It suggests that the results have significant implications for the field of study and may lead to further research in this area.

5. The fifth part of the document concludes the study. It summarizes the main findings and provides a final statement on the importance of the research.

SURFACE CHARACTERIZATION

Type and distribution of infiltration are functions of climate, topography and soils. Climate controls the potential recharge available to the system, topography determines how the potential recharge is redistributed at the surface, and the soil/rock framework controls what amount of the recharge actually enters the subsurface and what portion runs off in the surface hydrologic system. The presence of plants needing a constant or near constant water supply (phreatophytes) is an important indicator of discharge zones and a shallow water table. They often extend significantly the information obtained from the study of surface water features and springs. Consequently, the absence of phreatophytes is indicative of the absence of water near the surface. The following sections summarize the surface characterization at Carlsbad Cavern reported in Brooke (1996).

Climate

The amount of water available for infiltration in the subsurface is, among others, a function of various climatological factors. Especially important are amount and type of precipitation (i.e., rain and snow), precipitation distribution in time (storm duration, storm intensity, and storm frequency), and potential evaporation (as function of wind, temperature, and humidity). The weather at Carlsbad Caverns National Park has been recorded since April 1978 by National Park Service personnel at a weather station located just southeast of the maintenance yard. The climate is semi-arid with a bimodal precipitation distribution. The two peaks usually occur in July and September. The average annual precipitation amounts to 420 mm (16.45 inches). Most of this precipitation occurs in mid summer and early fall (Figures 6 and 7) from storms lasting about two hours on average. These summer rains are often intense. In the period October through March rain storms may last longer, although the rainfall is not as intense as in the summer. During these winter months, precipitation may take the form of freezing rain and, occasionally, snow. Only 1.3 mm (0.05 inch) falls on average during these winter events, versus 2.5 to 4.1 mm (0.10 to 0.16 inch) during summer storms. Due to these weather characteristics, flooding may occur during the summer months. Annual and monthly rainfall amounts may differ significantly from year to year and multi-year periods of less-than or above average rainfall have been recorded.

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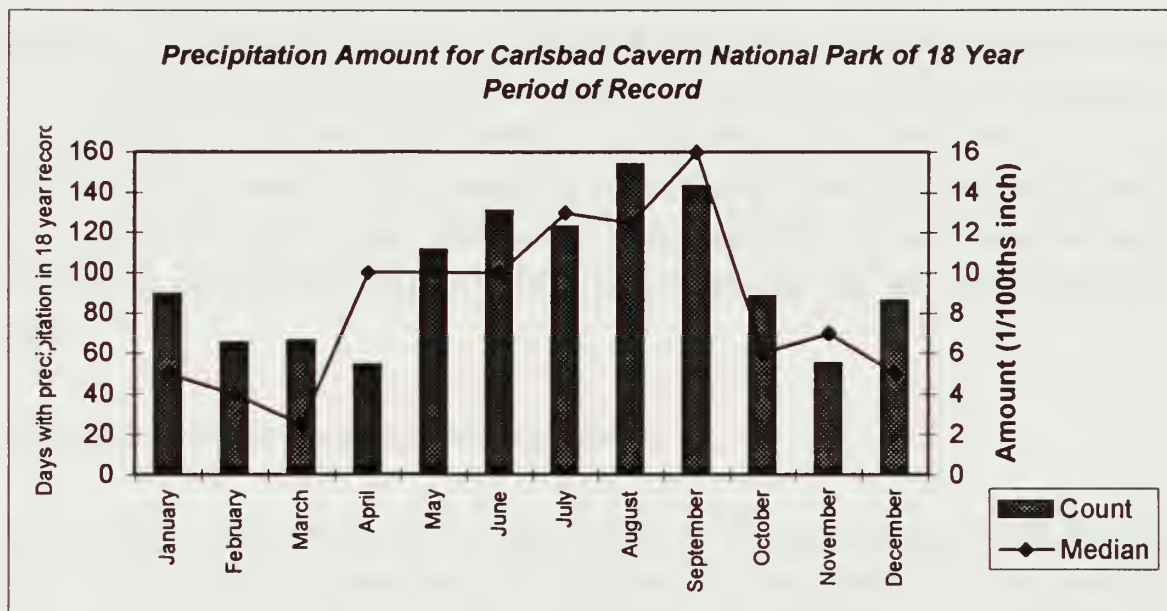


Figure 6: Average precipitation amount for 18 year period of record at Carlsbad Caverns National Park and number of days having precipitation for record (from Brooke, 1996)

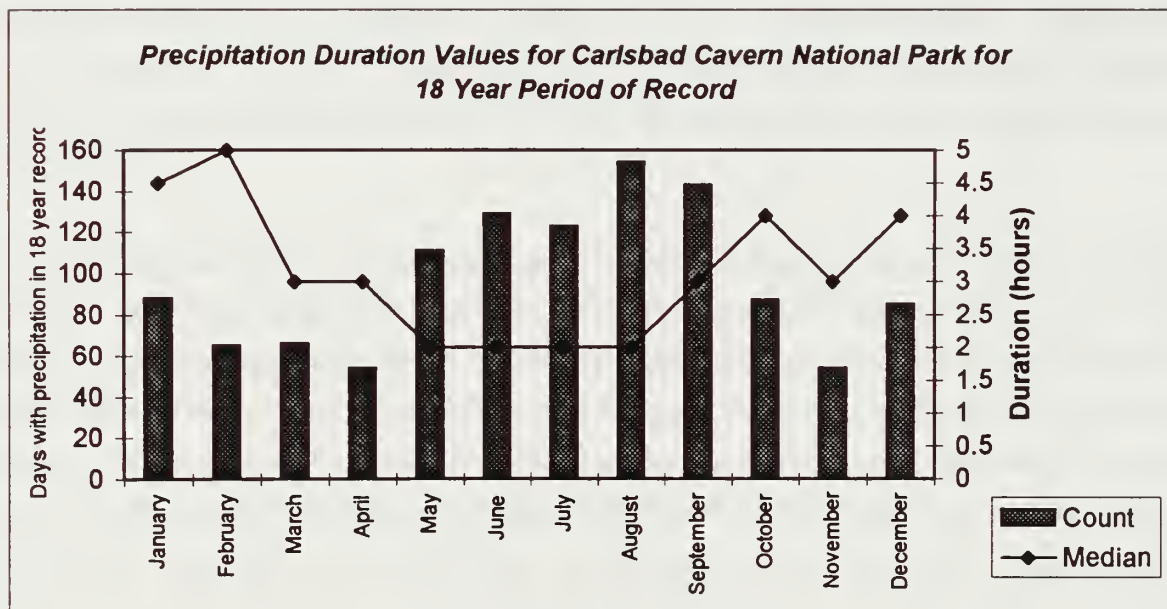


Figure 7: Precipitation duration for 18 year period of record at Carlsbad Caverns National Park and number of days having precipitation for record (from Brooke, 1996)

Kohler (1959) estimated that the generalized lake evaporation for this region is approximately 1780 mm (70 inches) per year. Because the average annual precipitation for this region is only 420 mm (16.45 inches) per year, there is a net water budget deficit of approximately 1360 mm (53.55 inches). Evaporation occurs primarily during the hot summer months, when water is available at or near the land surface during and after storms. During the cooler winter months, very little evaporation occurs and some recharge to the ground water system may take place, despite the low intensity of the storms in that period.

Topography, Surface Hydrology and Vegetation

The topography of the study area is characterized by a ridge, superposed on the regional basin. This ridge is intersected by a canyon and separated from the basin by an escarpment (Figures 1 and 8). The elevation of the land surface in the study area varies from a minimum of 1145 m (3760 ft) to a maximum of 1380 m (4520 ft), resulting in a maximum relief of 235 m (760 ft). The caverns lie in the south part of the ridge close to the escarpment and extend from the escarpment to the tributary drainages of Walnut Canyon. The ridges have their long topographic axis trending northeast-southwest, dipping gently to the northeast. Walnut Canyon, a synclinal valley north of the cavern, follows the structure of the Guadalupe Ridge and joins the Delaware Basin some distance to the east of the caverns.

Brooke (1996) performed a slope analysis to determine the amount and type of infiltration expected at the surface (see Figure 9). He distinguished three major types of slope-related infiltration characteristics: 1) diffuse infiltration on convex slopes ranging from almost flat to 10%, 2) focused infiltration on concave slopes ranging up to a maximum of 20%; and 3) limited infiltration and rapid surface runoff on slopes ranging from 20% to 50%. The first type of infiltration is present primarily in the highland areas. Areas that are considered to belong to the third type of infiltration may contain discontinuous cliffs. Surface runoff, occurring in this steep zone between the flatter higher and lower elevations, collects in the concave depressions where intermittent streams transport it out of the study area (Brooke, 1996).



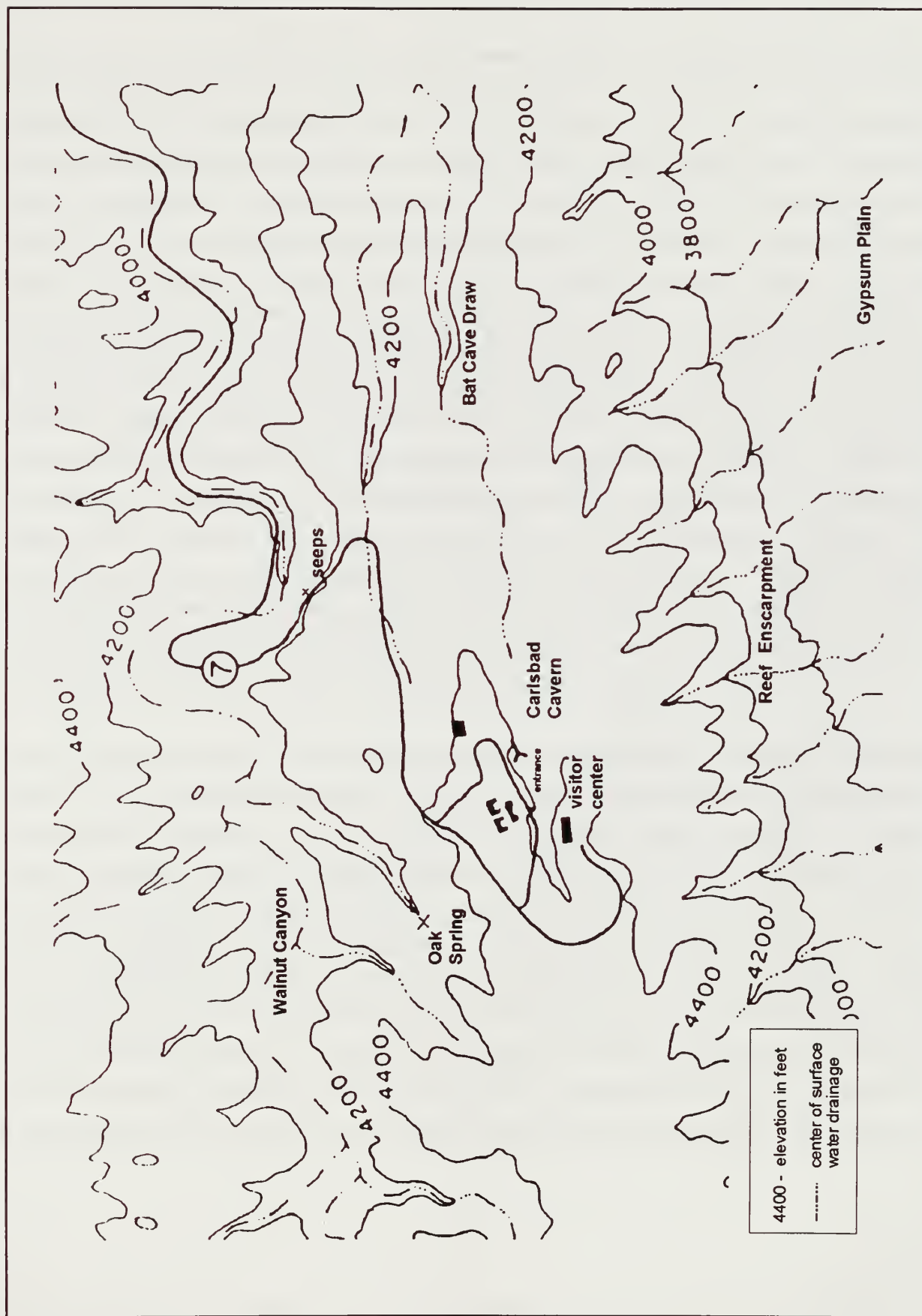
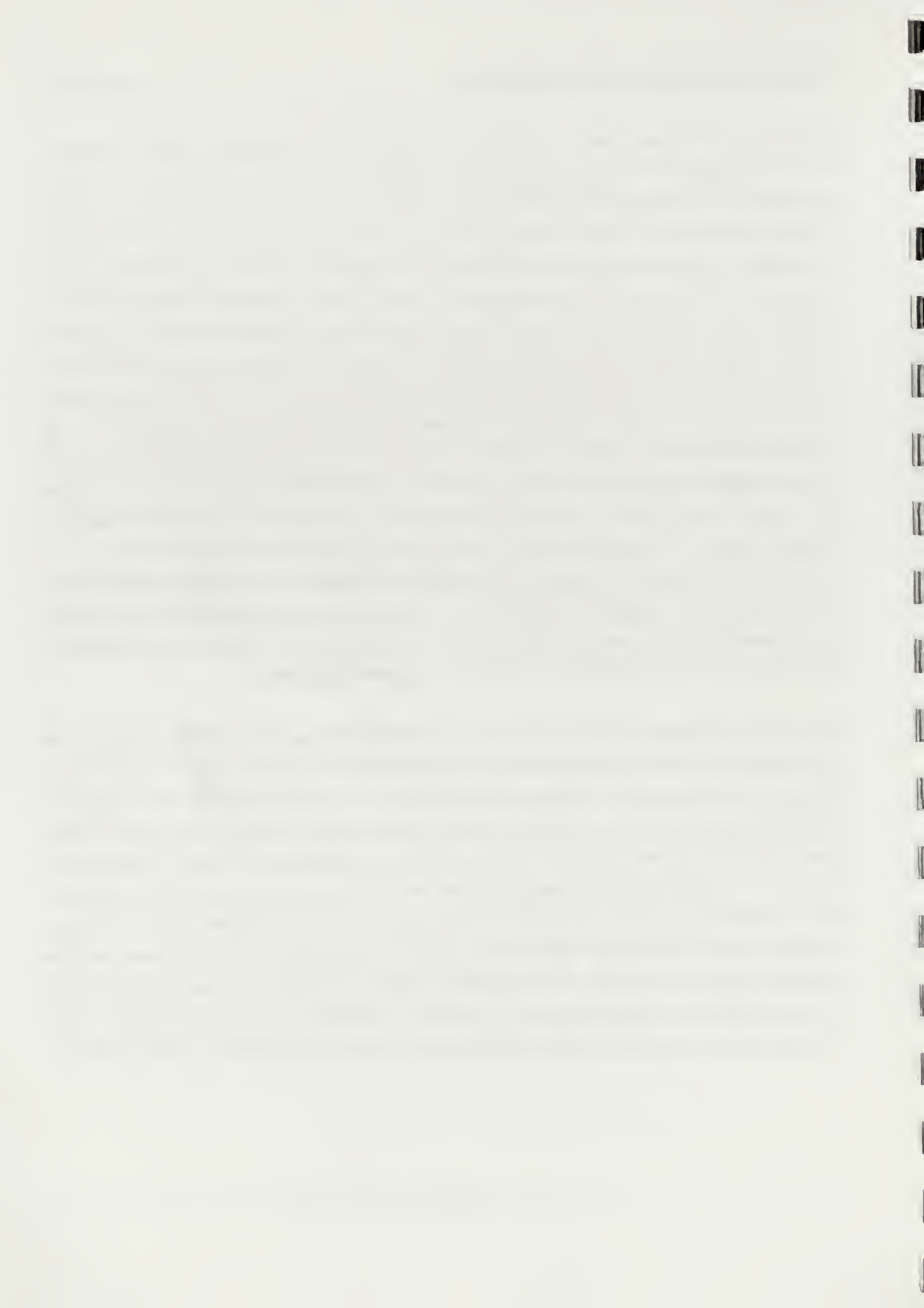


Figure 8. Topography and surface water distribution in the Carlsbad Cavern area (from Hill, 1987).

During most of the year, there is little surface water present in the study area. All streams flow intermittently and loose water due to infiltration into the stream beds. Surface discharge from the subsurface has only been observed along a line of springs and seeps located within Walnut Canyon at approximately 1280 m (4200 ft) in elevation. The spring line occurs where a low permeability layer at the top of the Yates Formation bisects the canyon wall. This backreef contact with the overlying Tansill Formation creates a perched aquifer at an elevation higher than the caves in Carlsbad Cavern located in backreef facies. A major surface discharge point along the spring line is the perennial Oak Spring, located in a prominent tributary to Walnut Canyon (Figure 9). In addition to this spring, there are rather continuous seeps at the Yates-Tansill contact located on the main road in Walnut Canyon, northeast of Carlsbad Cavern (Figure 9). During dry periods, the runoff on these seeps infiltrate back into the ground at a short distance downslope. This is also the case for Oak Spring. It should be noted that on the south side of the Guadalupe Ridge, lines of springs are present, including the perennial Rattlesnake Spring. The authors believe that these springs are not directly related to the local hydrologic system of Carlsbad Cavern, but are expressions of the regional (saturated) ground-water system and preferential flow zones caused by subsurface structures outside the study area (see the location of the water table in the alluvium aquifer in Figure 4).

Runoff in the drainages occurs only during rain storms because the surface of the lowest parts of the study area lies at least a few hundred meters above the regional water table. Most of the streambed in Walnut Canyon is filled with large cobbles and boulders, evidence that the canyon is subject to regular flash floods. According to Brooke (1996), such a flood occurred on July 5th, 1995, after a thunderstorm with highly localized rain showers. A large amount of precipitation fell in the upper drainages in Walnut Canyon, but no precipitation was recorded at the Carlsbad Caverns weather station. Brooke observed that most of the precipitation from these intense summer storms leaves the area as rapid surface water runoff. Only in rather flat areas, runoff may be slow enough to allow the precipitation to infiltrate into the subsurface. Recharge to the cave system is not hypothesized to occur from Walnut Creek as this stream is located away from the actual



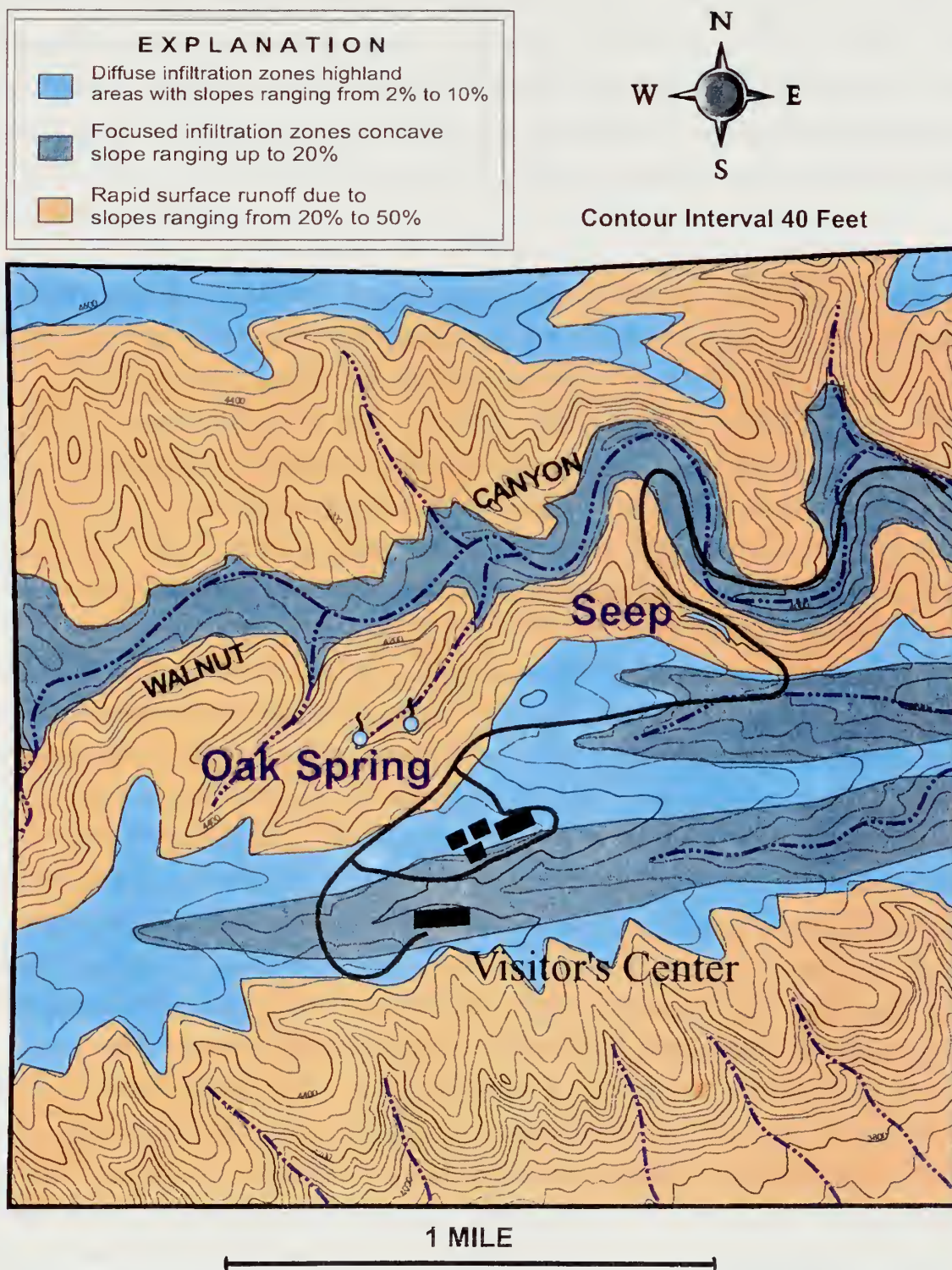


Figure 9. Surface infiltration type and distribution, and surface hydrology (from Brooke, 1996).

(known) caves and seems to be underlain by a perched water table (as indicated by the presence of many phreatophytes), probably located at a lithologic contact (see stratigraphic section in Bebout et al., 1993, p.34, and figure 17 in Hill, 1987). Walnut Creek water infiltrates into the canyon alluvium and moves downstream as shallow subsurface flow (interflow) towards White City. Between the study area and White City, most of the water probably percolates into the deeper formations to recharge the regional ground-water system.

The plants found at the study site are typical for the Chihuahuan Desert. The area is sparsely vegetated and shrubs and cactus are the dominant species in most of the study area. Field surveys performed by the authors confirmed sparse presence of phreatophytes, except for the Walnut Canyon and Bat Cave Draw bottoms, and areas around ephemeral and perennial springs and seeps. Some trees have established themselves in the drainages of the study area, and at isolated locations on the flatlands on top of the ridge. Some grasses are present in the drainage bottoms and along the ridges. In the study area, phreatophytes are indicative of the presence of perched water tables and related discharge features, of zones of focused infiltration, and of local areas where shallow barriers to infiltration increase the water content of the soil enough to sustain species that have moderate, rather continuous water needs. The latter mechanism is related to the presence of a subcutaneous zone near the surface (discussed on page 50). The major species present that rely on a constant source of water throughout the year are the oaks at Oak Spring. Some phreatophytes found in the study area are the little walnut trees along the stream channel in the bottom of Walnut Canyon, and some willows. The presence of these species in Bat Cave Draw and Walnut Canyon confirms the increased surface infiltration in these areas, determined in the slope analysis. Along the spring line in Walnut Canyon, including Oak Spring, phreatophytes and other species thrive (see dark colored bands in Figures 10 and 11). The presence of these species indicate a rather continuously available water supply at the Tansill-Yates Formation contact (see later in this report). The paucity of water loving plants over most of the study area signifies that the water table is well below root depth. Furthermore, concentrated surface runoff and subsequent (secondary) infiltration from parking lots and other closed surfaces are indicated by erosion features and locally increased density in vegetation (e.g., south side of Natural Entrance parking lot; see dark colored patches in Figure 11).

1. The first part of the document discusses the importance of maintaining accurate records of all transactions and activities. It emphasizes that proper record-keeping is essential for transparency and accountability, particularly in financial matters. The text suggests that organizations should implement robust systems to track every aspect of their operations, from procurement to sales.

2. The second section focuses on the role of technology in modern business management. It highlights how digital tools can streamline processes, reduce errors, and improve overall efficiency. The author argues that embracing technology is not just a competitive advantage but a necessity for long-term success in today's fast-paced market.

3. The third part of the document addresses the challenges of human resource management. It discusses the importance of attracting, developing, and retaining top talent. The text provides insights into effective recruitment strategies, performance management techniques, and the benefits of a positive work environment. It also touches upon the need for continuous training and development to keep the workforce up-to-date with industry trends.

4. The fourth section explores the significance of customer relationship management (CRM). It explains how understanding and responding to customer needs can lead to increased loyalty and sales. The author suggests that businesses should invest in CRM systems and training to ensure that every customer interaction is a positive one, leading to long-term relationships and repeat business.

5. The fifth part of the document discusses the importance of financial management and budgeting. It outlines the steps involved in creating a realistic budget and how to monitor financial performance against it. The text stresses that sound financial management is crucial for the sustainability and growth of any organization, providing a clear framework for decision-making and resource allocation.

6. The sixth section covers the topic of risk management. It identifies various types of risks that organizations may face, such as operational, financial, and reputational risks. The author provides a framework for assessing these risks and implementing effective mitigation strategies to minimize potential negative impacts on the organization.

7. The seventh part of the document discusses the importance of communication and collaboration within an organization. It emphasizes that clear communication channels and a collaborative culture are essential for achieving organizational goals. The text suggests that leaders should foster an environment where team members feel comfortable sharing ideas and feedback, leading to better problem-solving and innovation.

8. The eighth section focuses on the role of leadership in driving organizational success. It discusses the qualities and skills that effective leaders possess, such as vision, integrity, and the ability to inspire and motivate others. The author provides practical advice on how leaders can build strong teams, make strategic decisions, and navigate challenges with confidence.

9. The ninth part of the document discusses the importance of innovation and continuous improvement. It explains how organizations can foster a culture of innovation by encouraging creative thinking and experimentation. The text suggests that regular reviews and feedback loops are essential for identifying areas for improvement and implementing changes that drive growth and innovation.

10. The final section of the document provides a summary of the key points discussed and offers concluding thoughts on the overall success of an organization. It reiterates the importance of a holistic approach to management, where all these factors—records, technology, HR, CRM, finance, risk, communication, leadership, and innovation—are integrated to achieve the organization's mission and vision.

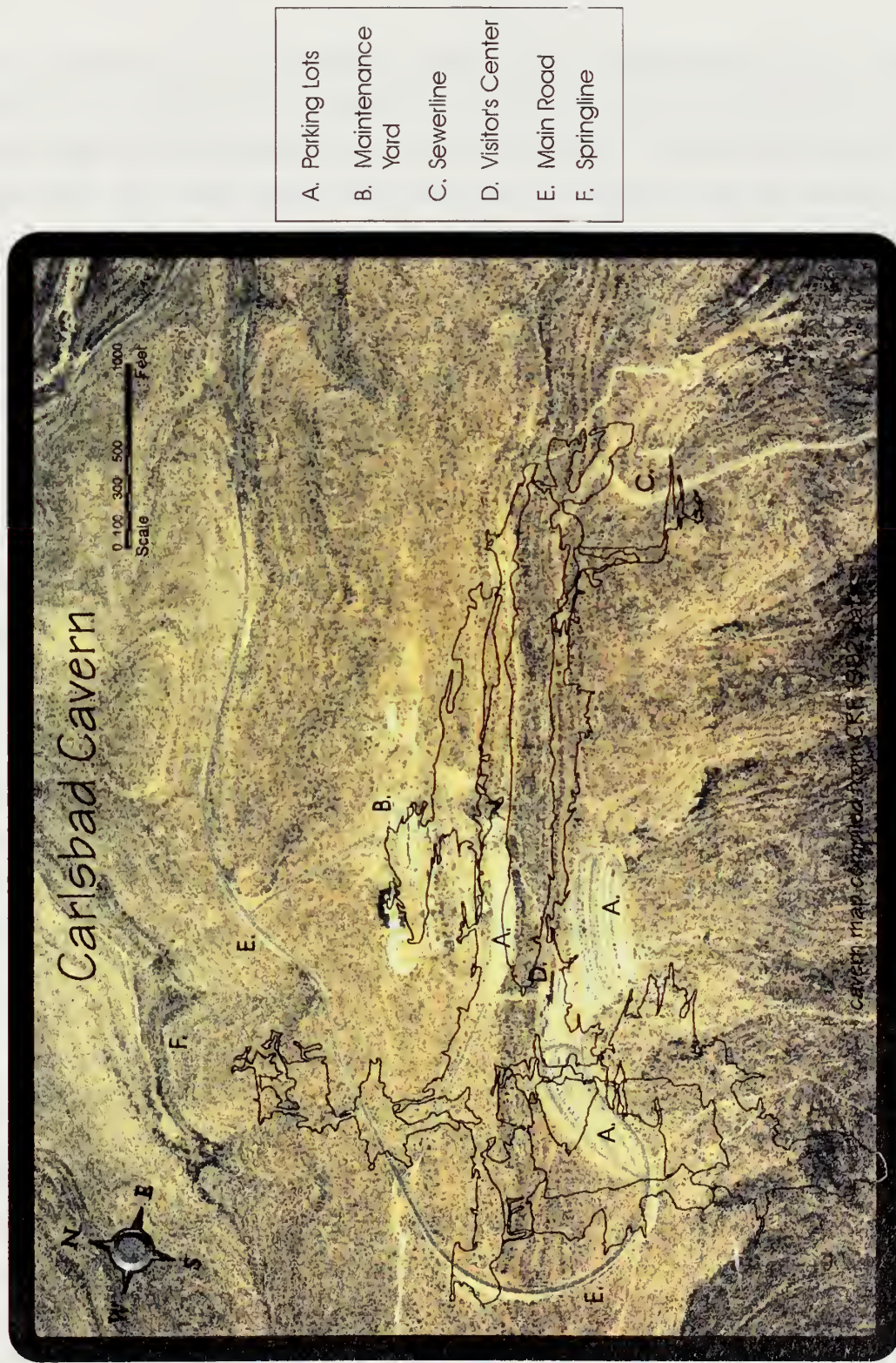


Figure 10. Carlsbad Cavern superposed on aerial photo of study area (from Brooke, 1996).

Soils

The study area is geomorphologically characterized by the limited extent of soils and other geomorphic deposits. In many parts of the study area, soils are very thin or absent due to the presence of limestone bedrock near the surface. Generally, limestone does not provide much base material for soil forming due to dissolution during its weathering. In the absence of major soil layers, overland flow resulting from intense summer storms removes most of the non-dissolved weathering products, especially on the moderate to steep slopes. During dry periods, the desiccated topsoil, when present, is subject to removal by wind. This is particularly the case at the higher elevations due to the sparsity of vegetation. Locally, soil filled cracks are present in the bedrock, retaining enough moisture for some sparse vegetation and providing important entry points for surface infiltration. In the drainage bottoms some soils have been established and vegetation is more developed.

Although the Guadalupe Ridge is a prime karst development area, most of the karst features in the study area are restricted to the subsurface. Brooke (1996) attributed this to the arid climate that this region has experienced since Pleistocene time. He also suggested that the more dolomitic Tansill Formation acts as a cap rock over the purer limestone in the Capitan Formation below. Karst collapse features are present in Walnut Canyon to the east of the intersection of the Loop Road and the Main Road, and at the Natural Entrance to the caverns. The colluvium found in the latter collapse collects runoff entering the cavern during some intense storms in the area from where it infiltrates into the underlying limestone through a network of fractures and solution channels.

Anthropogenic Effects

To determine the anthropogenic factors of importance to this study, sources of contamination have been identified (Figure 12) and hydrologic effects of man-made changes in land-use have been assessed. Such hydrologic effects include diversion and concentration of natural runoff from altered surfaces, slopes, drainages, and roads, increased evaporation from man-made surfaces, reduction and diversion of infiltration caused by buildings, parking lots, and roads, and water discharges, such as water fountain runoff, sewer line leaks, and water main breaks.



Figure 11. Aerial photo of Carlsbad Cavern area with location of Park facilities.

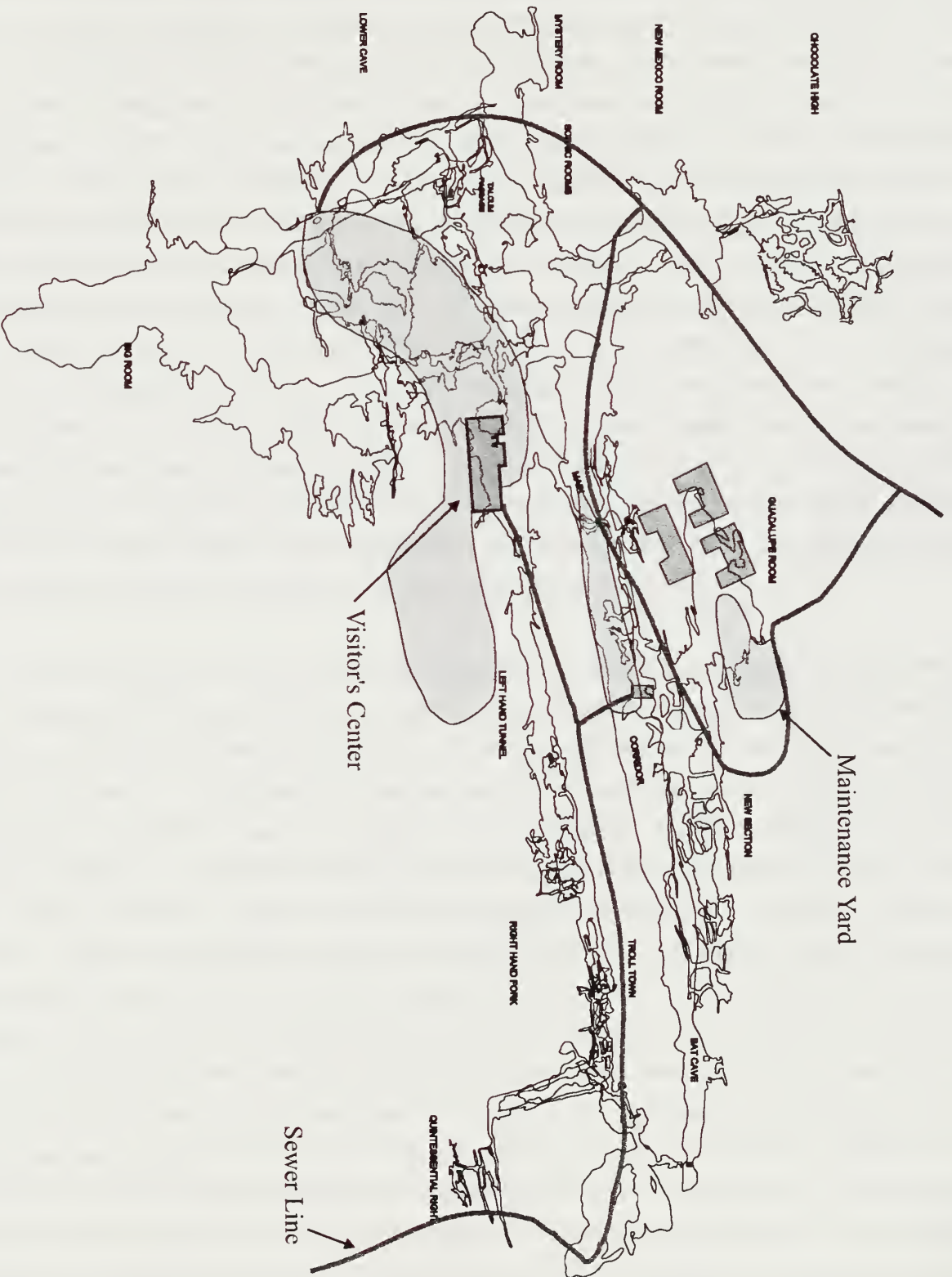


Figure 12. Surface facilities and cave geometry at Carlsbad Cavern (from Brooke, 1996).

Major anthropogenic activity started in the early part of the 20th century in the form of bat guano mining. Originally, the guano was removed through the Natural Entrance to the cave. Around the turn of the century, a mine shaft was dug in the eastern end of Bat Cave. The guano mining was discontinued before the area was designated a National Park by Congress in 1930. The mine shaft was closed by the National Park Service in the early 1980's. In the 1930's, the Civilian Conservation Corps built an extensive trail network at Carlsbad Cavern and constructed many of the present-day buildings. An elevator shaft was constructed from the visitor's center to the underground lunchroom at the entrance to Left Hand Tunnel in the early 1930's, and then a second shaft was built immediately to the east of the previous one in the mid 1950's. The last major construction in the study area was the enlargement of the visitor's center, maintenance yard, and the creation of dormitories in the 1960's. Most of the infrastructure lies directly above the caverns, including three paved public parking lots, the visitor's center, a maintenance yard consisting of a paved area and various buildings, an unpaved storage area near the maintenance yard, staff housing, and offices (Figures 11 and 12). The visitor's center, Park offices and housing are serviced by a water main and sewer lines.

The sewer lines (Figure 12) are potential sources for cave contamination, among others by nitrate and Total Organic Carbon (TOC). The sewer lines collect effluent from the staff housing, maintenance yard and offices in a pumphouse located immediately west of the Natural Entrance. This effluent is then pumped southward almost across Main Corridor to the south side of Bat Cave Draw, where it joins a sewage line from the visitor's center. The latter follows a route south of Bat Cave Draw directly above Left Hand Tunnel. From the junction of the two lines to a point southwest of the Natural Entrance, the effluent continues along the southern side of Bat Cave Draw until it meets a newer sewer line constructed in the 1970's. From this point over the Lake of the Clouds area of Carlsbad Cavern, south of the guano shaft, the sewage line curves southward across the ridge and down the escarpment into sewage lagoons in the Delaware Basin. The older sewage line consists of a four-inch unlined clay pipe, lying unsealed, end-to-end, in four-foot sections and has been subject to breaks and leaks. Both old and new lines have clogged and overflowed repeatedly (National Park Service personnel, pers. comm.). Due to this history, these sewer lines may be a source of nitrate and metals within some parts of the vadose zone and the caves for some time. Furthermore, a potential source is provided by a utility

shaft near the elevator shafts underneath the visitor's center containing, among others, pressured pipe lines to bring sewage from the underground service area to the sewage lines at the surface.

Other potential contaminant sources at the site are the aboveground and underground storage tanks found at various locations. At the maintenance yard, a buried diesel tank and propane tanks are present. Propane tanks are also present near some of the housing units. In the past, a gas station was located at the Bat Cave parking lot (National Park Service personnel, pers. comm.). Behind the visitor center is a storage tank for a backup power generator.

In addition to their potential for generating contamination, many of these structures redistribute and focus runoff and the contaminants that it may contain. Specifically, the parking lots and the paved surface of the maintenance yard collect materials such as motor oil, antifreeze, metals, and solvents in storm drains leading directly into the Bat Cave Draw area.

In addition to accidental releases of contaminants occurring in or around these man-made structures, contamination of cave water from the land surface may result from certain practices that affect the hydrology and infiltration of water, or cause incidental or chronic chemical releases. These practices include maintenance of private gardens (increased infiltration of water, percolation of excess fertilizers and pesticides), salting of roads and trails during the winter months, use of water, solvents and cleaners in the maintenance yard to clean vehicles and equipment, and allowing vehicles that may release oil, gasoline, and antifreeze onto the parking lots in areas directly above the caverns.

Surface Infiltration Type and Distribution

Diffuse surface infiltration takes place above most of the cavern (Brooke, 1996). Walnut Canyon, Bat Cave Draw and the drainage immediately to the north of the Draw are subject to more focused infiltration (Figure 9). The areas to the north and south of the diffuse infiltration zones experience rapid surface runoff due to steep slopes and are considered insignificant with respect to infiltration.

SUBSURFACE CHARACTERIZATION

Geology (Lithology, Stratigraphy, Structure)

The geology of the study area is characterized by the presence of historic and current karst activity (dissolution and secondary precipitation of carbonate rock) and resulting cave formation in an uplifted ridge of massive reef and bedded backreef limestone of Permian age. Most current solution activity is restricted to recently opened microfractures. Historic solution activity took place under much wetter conditions than are present today and have resulted in a complex system of interconnected cavities of varying size and at different depth. The generalized geologic cross-section is characterized (see Figure 4) by the absence of a continuous soil layer, the presence of a thin, exfoliated, open rock layer on top of an irregularly distributed layer of siltstone, in turn underlain by thinly bedded limestone with very few karst features (Tansill Formation; serves as a discontinuous caprock against erosion), the somewhat karstic backreef units with fine-grained interlayers (Yates Formation and Seven Rivers Formation) and, finally, the cavernous, fractured, massive reef and brecciated forereef limestone (Capitan Formation). Table 1 lists some more features of these formations. Hayes (1964) reported that the dolomitic Yates Formation is similar in composition and lateral variability as the underlying Seven Rivers Formation, but that the Yates Formation includes persistent sandstone and siltstone layers that act, together with the Tansill Formation, as a caprock protection for the more soluble Seven Rivers Formation. The extent of the Seven Rivers Formation in the study area is not established (Hill, 1987). The top of the Yates Formation is defined by a rather continuous, orange-colored siltstone layer. The thin to medium-bedded dolomitic Tansill Formation contains also various discontinuous siltstone layers, ranging from 1/3 to 1 m (1 to 3 ft) thickness and vertically spaced between 2.5 and 7 m (8 and 21 ft). These siltstone layers are present throughout the study area. The presence of the sandstone layers in the Yates Formation also distinguishes it from the Tansill Formation (Brooke, 1996). The prominent bedding of the backreef formations is clearly visible in Walnut Canyon (Figure 11). The Guadalupe Escarpment, oriented southwest-northeast at the southern edge of the study area, represents the exposed edge of the massive part of the barrier reef (Capitan Formation), formed along the margin of a shallow inland sea located in the Delaware Basin. The majority of the caves in the study area are located within this

| Backreef Facies | | Reef Facies | Forereef Facies | Guadalupe Series |
|-----------------|------------------------|----------------------------------|------------------------------------|------------------|
| Artesia Group | Tansill Formation | Capitan Limestone Massive Facies | Capitan Limestone Foreslope Facies | |
| | Yates Formation | | | |
| | Seven Rivers Formation | | | |

| <i>Formation</i> | <i>Thickness</i> | <i>Description</i> |
|------------------------------------|------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Tansill Formation | 85-100 meter (250-300 foot) | Thinly laminated dolomite/limestone interbedded with discontinuous siltstones, highly fractured with 0.6 to 2.6 meter (2 to 8 foot) spacing, discontinuous |
| Yates Formation | 125 meter (375 foot) | Interbedded dolomite/limestone with brownish sandstones and siltstones |
| Seven Rivers Formation | 110-200 meter (335 - 600 foot) | Interbedded dolomite/limestone |
| Capitan Limestone massive facies | 250-335 meter (750 - 1000 foot) | Massive organic limestone formed from reef growth. Highly fractured, continuous with massive karst solution features |
| Capitan Limestone foreslope facies | 250-335 meter (750 - 1000 foot) | Bedded slope deposits of detrital fragments interbedded with reefal boundstone |

Table 1: Geologic units and descriptions (from Brooke, 1996)

unbedded, finegrained limestone. Figure 4 schematically shows the ragged contacts between the Capitan Formation and the backreef and foreslope facies due to the gradual prograding development of the Capitan Formation. A more detailed discussion of aspects of the lithology relevant to this study can be found in Brooke (1996).

Fracture density, connectivity and aperture depend on such variables as proximity of topographic surface or karst cavity, proximity to regional fracture zones, regional and local stress and strain history, facies of material, anthropogenic activity (earth moving, blasting), and bedding plane considerations. Fracture patterns are recognized both on the regional scale, and the local scale. Most fractures are pressure-closed or sealed; open fractures occur in rock-stress/strain related patterns as indicated by surface lineaments and subsurface dissolution features (Figure 13).

The Guadalupe Ridge is a large anticline structure extending from the Guadalupe Mountains dipping gently to the northeast. A complementary syncline to the north is occupied by Walnut Canyon. Bat Cave Draw is a smaller synclinal structure within the larger Guadalupe Ridge anticline and is situated between the two main east-west passages of the cavern. These smaller structures and associated stress fields have affected the hydrology of the cave system. Both northwest-southeast and northeast-southwest stress/strain trends are present, influencing the distribution and orientation of open versus closed fractures. Typically, open fractures are encountered near the surface at the top of anticline structure; in syncline structures such fractures are often closed. However, with depth, fractures in syncline structures are subject to less stress or even increased strain, especially where they intersect cavern space. Brooke (1996) plotted the joints in both the surface and subsurface in the study area (Figure 14). There are two observed joint orientations. The major orientation of the joints is between N70°E and N90°E. A second significant orientation lies between N30°W and due north. Together, these orientations account for 70% of the data. These results correspond to those found by Tallman (1993) in a regional study including the study area. Local joints have the same orientation as the major caves, and both joint and cave orientation follow regional structural trends. This is evident when joint and cave orientations are compared with the orientation of the Guadalupe Ridge, a regional structural feature. The dominant joint and cave orientation is parallel to the ridge axis, while the second major orientation is

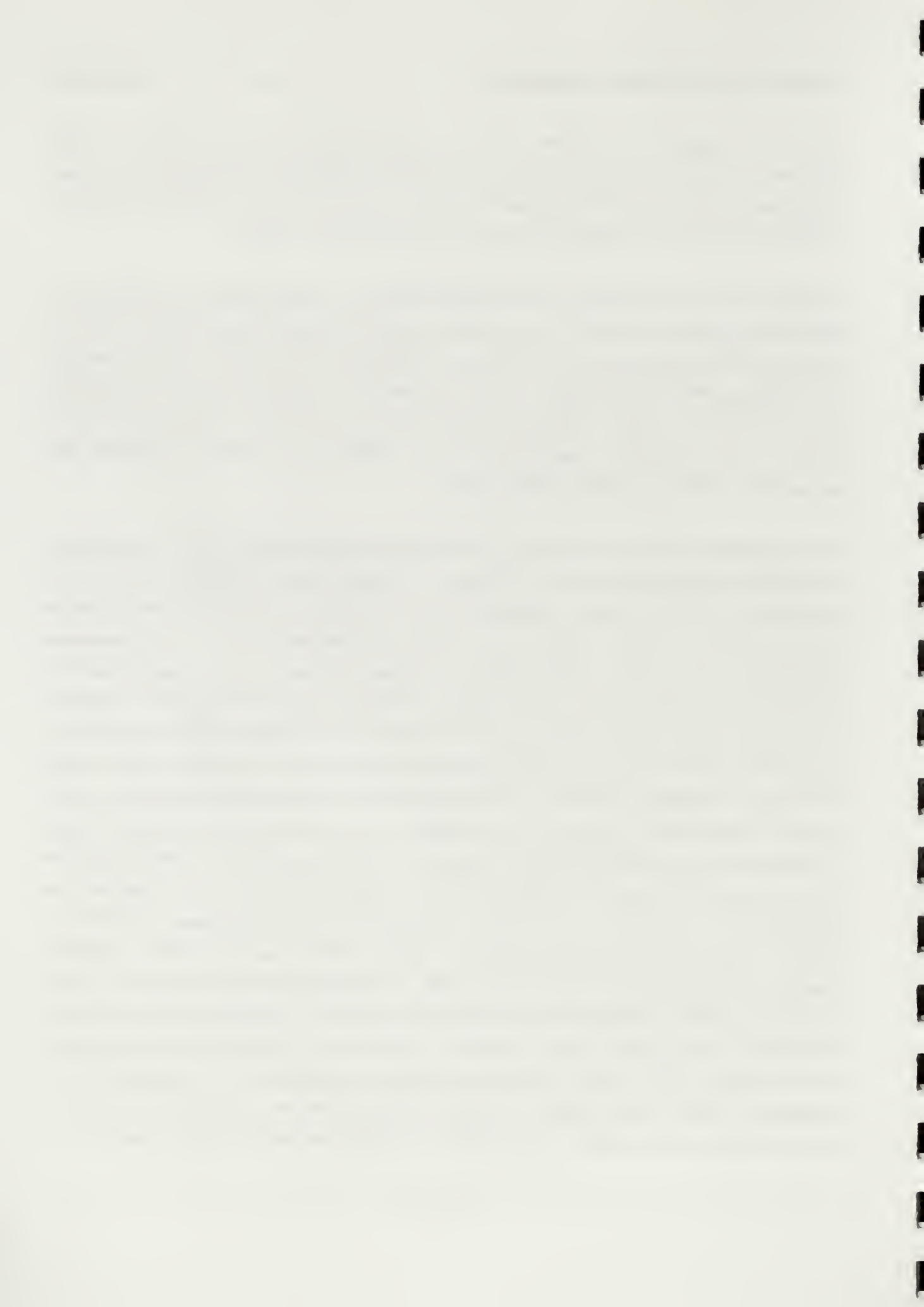




Figure 13. Carlsbad Cavern lineament data (from Brooke, 1996).

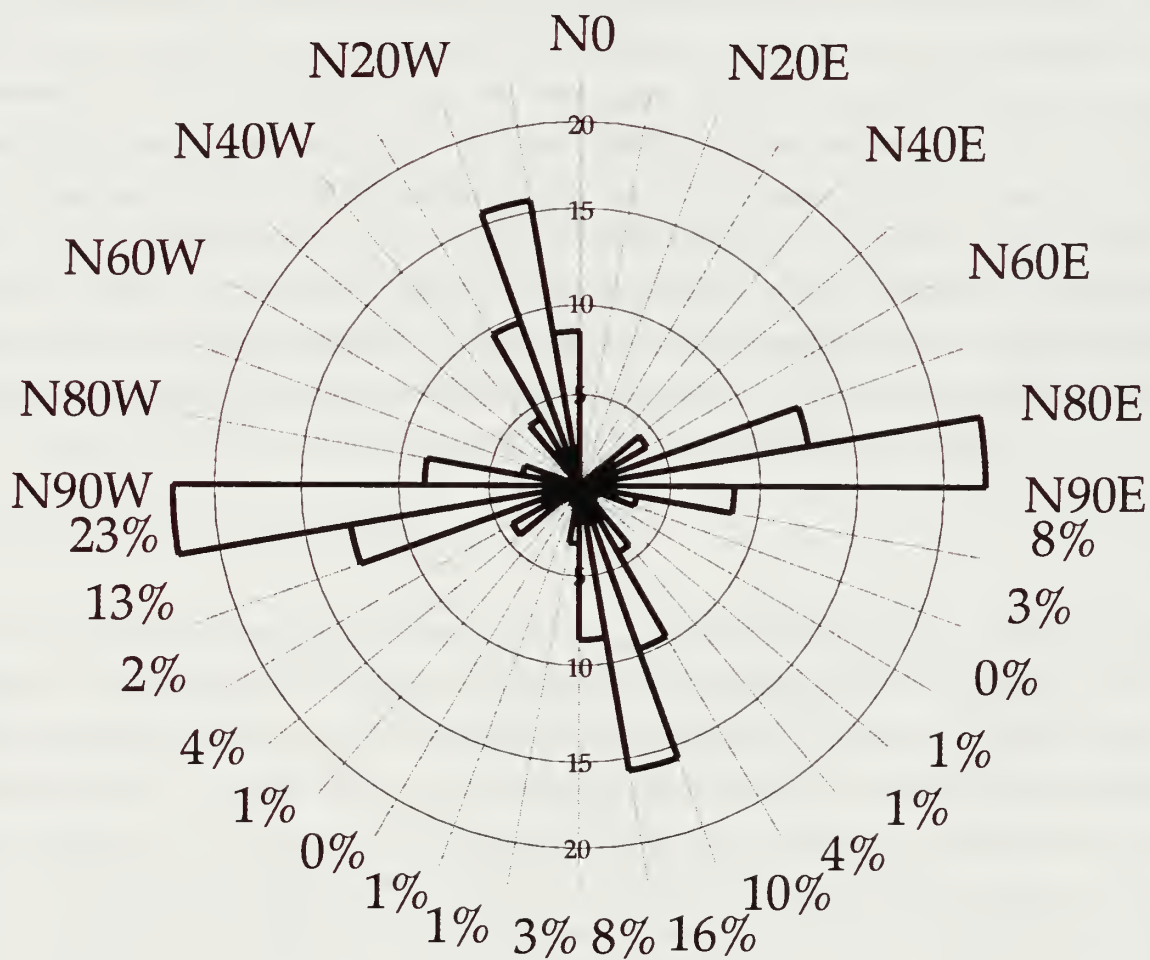


Figure 14. Rose diagram of surface and subsurface joint data for Carlsbad Cavern (from Brooke, 1996).

perpendicular to this axis. The caves oriented parallel to the ridge axis are located away from areas of maximum stress and strain. Brooke (1996) suggested that their formation might be more related to formation contacts than to fracture patterns.

The geologic framework is characterized by the geometry resulting from reef growth in Permian time and subsequent uplift and folding of the Guadalupe block in Cenozoic time. This has resulted in the preferential joint orientation, present in the study area. The continuity, frequency, and hydraulic effectiveness of these joints are controlled by the competence of the rock layers and the magnitude of the stresses and strains to which these layers have been subjected. Brooke (1996) noted that within the massive member of the Capitan Limestone, these joints are relatively continuous and may extend 33 m (100 ft) or more, but that the fractures in the dolomite/limestone layers of the Tansill Formation are less continuous, due to the presence of local siltstone layers. The backreef facies are thinly-bedded, containing alternating layers of dolomite/limestone, sandstone and siltstone. Each of the backreef formations has a different competency and, consequently, the degree of jointing, the extent of individual joints, and their hydraulic effect varies.

Subsurface Anthropogenic Effects

There are several anthropogenic structures located within the subsurface that can affect the amount and distribution of water infiltrating into and through the subsurface. Most of these structures are the result of the infrastructure required for the support and comfort of the cave visitors. A major factor in the redistribution of percolating water is the presence of an extensive trail system and the virtually impervious lunchroom area at about 250 m (750 ft) below the visitor's center. Cleaning the trails and the lunchroom area with water may contribute to additional downward percolation, as well as contamination of the underlying rock and caves. Brooke (1996) noted that part of the underground trails consists of an asphalt top that is bound with an epoxy in an attempt to reduce the amount of gravel being swept and washed off the trail into the surrounding caverns. Not only is water released for this periodic cleaning, the water lines along the trails leak water at connection points and spigots at an unknown rate. The resulting runoff from the trails may contain rocks, unspecified organic compounds, and nitrate from visitor's urinating on the trail (National Park Service personnel, pers. comm.).

Another concern results from the presence of the elevator and utility shafts underneath the visitor's center. These shafts provide major downwards pathways (and shortcuts) for water infiltrating in the upper formations, as observed during the study (Brooke, 1996). Restroom facilities are located within the lunchroom area. A sewage pump removes the wastewater through the utility shaft to the surface. Contamination may result from a maintenance or breakdown of these restroom and sewage transport facilities. The locations of the underground lunchroom, restroom facilities and elevators are shown in Figure 3.

HYDROCHEMICAL CHARACTERIZATION

A hydrochemical characterization of the study area was performed by Brooke (1996). Eighty-five water locations were sampled, four of which were taken at the surface. Most of the subsurface samples were taken from pools near drips, twenty-two were taken directly from drips. Furthermore, samples were taken from parking lot and maintenance yard runoff, Oak Spring, and the runoff in Bat Cave Draw near the Natural Entrance. Samples were analyzed for both major-ions and trace metals. Data quality was evaluated through the analysis of duplicates for about a quarter of the samples. Statistical evaluation of the hydrochemistry of surface and subsurface water showed that drip water and pool water within the Cavern represent the same population, but that cave waters and surface runoff come from statistically different sample populations. The concentrations of some aqueous species, for example, aluminum, zinc, nitrate and Total Organic Carbon (TOC) are significant higher in surface runoff compared to cavern waters. Still, Brooke (1996) suggested that the surface runoff may be a source for the anomalous hydrochemistry values detected in some of the cave drips and pools, specifically with respect to TOC, aluminum, manganese, and zinc. The lower concentrations in cave waters can be explained by the mixing of water from the parking lots with water from other surface areas that may take place during surface runoff before the subsequent focused infiltration. Specifically, this may apply to Bat Cave Draw.

Brooke (1996) selected for further spatial analysis four chemical compounds locally found in the cave waters in anomalous concentrations and known to be present in anthropogenic sources: aluminum, zinc, TOC and nitrate. For example, the results of the analysis of drip samples indicate the presence of high nitrate levels in some areas. Nitrate levels are elevated in some of the pool samples as well. High nitrate concentration is an indication of contamination by sewage or bat guano (Drever, 1988). Analysis for aluminum and zinc showed concentrations in the surface runoff with mean values of 4300 ppb and 380 ppb, respectively. Brooke (1996) mentioned that sources of these metals may be found in leached radiator fluid, and in asphalt, solvents, and detergents. High concentrations of Total Organic Carbon (TOC) in the surface runoff may be associated with asphalt, motor oils, solvents and detergents.

By plotting the results of the sampling and chemical analyses, Brooke (1996) showed that the spatial distributions of aluminum, zinc, total organic carbon, and nitrate correlate to sources of these compounds at the surface. For each of these four species, maps with their distribution in cave waters were overlain with maps of potential anthropogenic sources and cavern layout (Figures 15, 16, 17 and 18). Sample locations with aluminum, zinc, and nitrate concentrations in the ninety-fifth percentile and TOC concentrations in the ninetieth percentile are shown as solid diamonds. Brooke (1996) noted a clustering of high aluminum values in the Quintessential Right and Lake of the Clouds portion in the far eastern part of the Carlsbad Cavern (Figure 15). There are also high values of aluminum found in sections of the New Mexico Room, the Mystery Room, Main Corridor, and Lower Cave. The highest recorded value for aluminum was found in a pool in the New Mexico Room (455 ppb). Other high values were recorded in a drip in the Main Corridor (130 ppb) and in a pool in the Mystery Room (134 ppb). All these locations have surface structures directly over them. Brooke (1996) noted that the drip showing the high value in the Main Corridor, is located directly under the Natural Entrance parking lot.

The distribution of zinc in the caves shows a pattern similar to that of aluminum (Figure 16). The highest zinc concentrations were found in drip samples from the Quintessential Right, the Big Room, Main Corridor, Left Hand Tunnel, and a location in the New Section. The highest zinc concentration was found in the Talcum Passage (78 ppb). In addition to sampling surface runoff, Brooke (1996) also analyzed the Park's tap water for zinc and found a concentration of 205 ppb. This tap water is also used to spray down the cavern trail system, and is present in the sewer system as well. As in the case with aluminum, the areas with high zinc concentration within the caves are located directly below surface structures. Brooke (1996) noted that an additional source of zinc are the pennies thrown into pools near the main trail by visitors. However, he did not believe that this practice accounts for the high concentrations found in drips or pools within areas off limits to unsupervised visitors.

Brooke (1996) found that in Carlsbad Cavern the distribution of Total Organic Carbon (TOC) is fundamentally different than the distributions of aluminum and zinc. The highest values of TOC were found primarily in the eastern portions of Carlsbad Cavern. Only one high value was detected elsewhere (the New Mexico Room; Figure 17). High TOC values

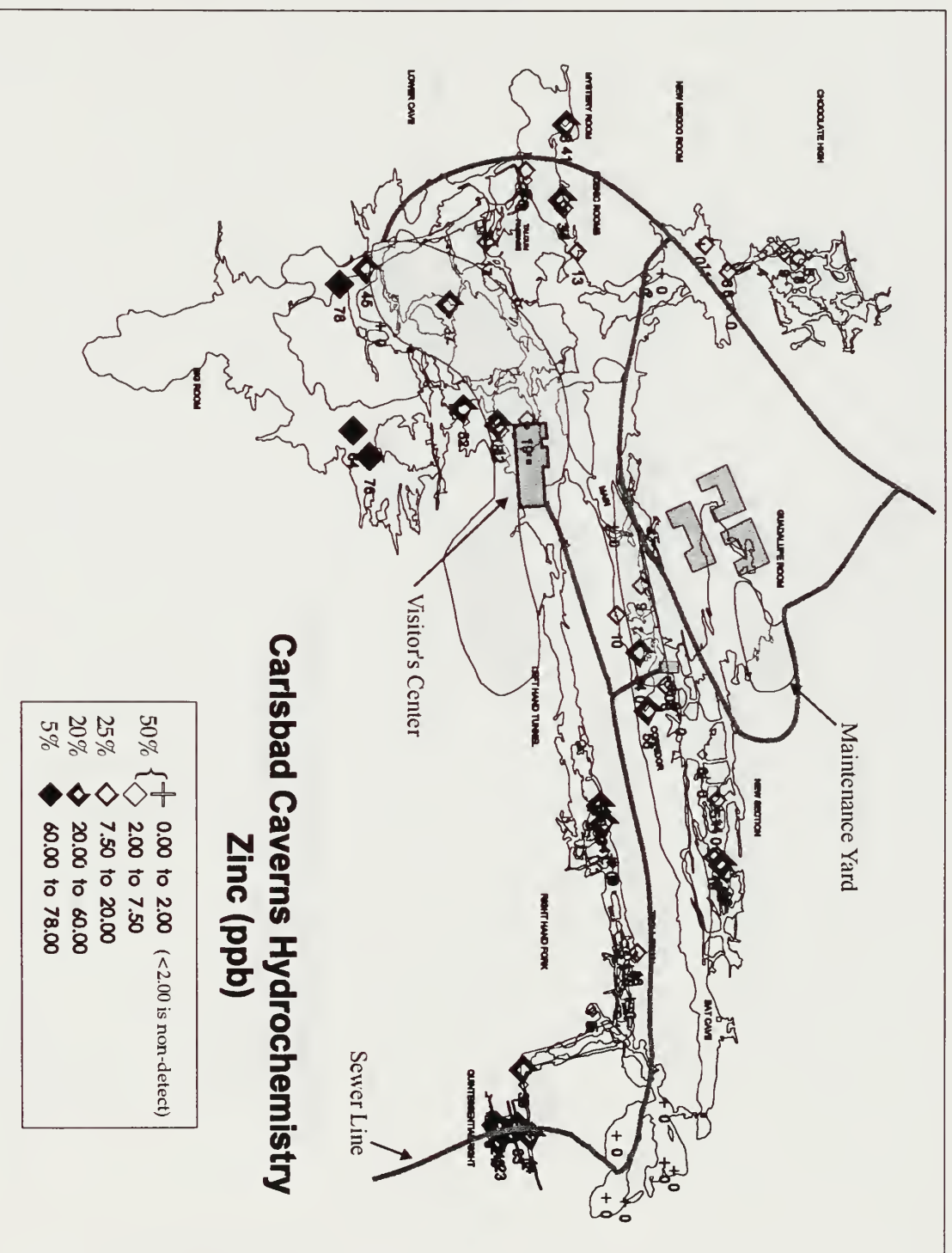


Figure 16. Carlsbad Cavern zinc hydrochemistry (from Brooke, 1996).

were specifically found in a limited section of Left Hand Tunnel, Right Hand Fork, and Quintessential Right. These values found here range from 12 to 21 mg/l, two to four times the mean cavern value. A sample taken in the Main Corridor, as National Park Service personnel were hosing down the Natural Entrance trail, showed a TOC concentration of 40 mg/l, indicative for the potential of trail maintenance as a source of contamination of lower cave levels. Some other significant TOC values (higher than 12 mg/l) were found in the Big Room, Mystery Room, New Mexico Room and Chocolate High. Brooke (1996) mentioned several potential sources for the elevated TOC values in cave waters, especially surface runoff (mean TOC value of 87 mg/l), and bat guano and bat remains in the cavern. The later source exists predominately in the Bat Cave. Furthermore, Brooke (1996) related some of the high TOC levels to locations where the sewer line passes directly overhead (Figure 17). Sewage is a known source of TOC.

Finally, Brooke (1996) discussed the distribution of nitrate in the Cavern. High nitrate values were found almost exclusively in the eastern portion of the Cavern, specifically in the eastern section of Left Hand Tunnel, Right Hand Fork, Bell Cord Room, and lake of the Clouds. In these areas nitrate concentrations range from 20 mg/l to 238 mg/l (compared with a mean value of 16 mg/l), with the highest values found in bell Cord Room and Lake of the Clouds area. A few other, isolated samples near the Natural Entrance in the New Section and the Main Corridor also contained high nitrate concentrations (ranging from 31 mg/l to 163 mg/l). Finally, a sample taken from Rookery pool, located in the Lower Cave, showed an elevated nitrate value of 30 mg/l. According to Brooke (1996), possible sources of nitrate in the cavern system include bat guano and leaking sewer lines. In most of the locations with high nitrate levels, the sewer line overlaps areas known to contain large amounts of bat guano (Figure 18). However, near the Natural Entrance in the Main Corridor, major bat guano deposits are absent. Here, the most likely source is sewage as several sewer lines intersect in the area and a sewage pumphouse is located nearby. In the New Section, some of the elevated nitrate levels may be due to washing off of the trails.

HYDROLOGIC SYSTEM ANALYSIS

The local hydrologic system can be considered a non-subordinate system of the regional hydrologic system, in the sense that very few features of the regional hydrologic system (both surface water and ground water) influence the flow rates and flow paths in the local hydrologic system. This local system is characterized by rapid surface runoff, limited infiltration into the subsurface, and thick layers of fractured and karstic rock subject to variably saturated downward flow, sometimes interrupted by perched conditions with primarily lateral flow. Infiltration takes place at rather flat surfaces at the top of the ridge, and in depressions, gullies and creek beds. During some rainstorms part of the surface runoff is channeled to cave entrances and infiltrates in the floor of nearby cave passages. Except for small discharge areas indicated by seeps and springs, most of the study area is considered a recharge area for the regional ground-water system (Tallman, 1993). The water-table at the site is reported to be located below 1065 m (3200 ft), about 365 m (1100 ft) below the Natural Entrance (Figure 4).

Hydrogeology

According to Brooke (1996), the study area contains seven distinct hydrogeologic units (Table 2): 1) Walnut Canyon Alluvium, 2) Tansill Dolomite and Siltstone, 3) Yates Siltstone, 4) Yates Sandstone and Dolomite, 5) Seven Rivers Dolomite, 6) Massive Capitan Limestone, and 7) Foreslope Capitan Limestone. The Walnut Canyon Alluvium is a Quaternary deposit consisting of alluvium within Walnut Canyon and has a relatively high permeability (Table 2). The top of the hydrogeologic profile is characterized by the absence of a continuous soil layer, the presence of a thin, exfoliated, open rock layer on top of an irregularly distributed highly impermeable layer of siltstone, in turn underlain by rather impermeable limestone with very few karst features (Tansill Formation). The Tansill Dolomite and Siltstone is composed of thinly bedded, dolomitized limestone between discontinuous siltstone layers and is located over the other hydrogeologic units. The presence of low-permeability interbeds (siltstone and the lower part of the subcutaneous zone) near the surface, within the Tansill Formation and at the formation contacts has a major influence on the flow regime. The Yates Siltstone consists of a low permeability siltstone bed at the top of the Yates Formation. The Yates Sandstone and Dolomite,

Table 2. Hydrogeologic units and properties (after Brooke, 1996).

| Hydrogeologic Unit | Description | Thickness ¹⁾ | Primary Porosity (fraction) | Primary Permeability m/day (ft/day) ¹⁾ |
|--------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------|---------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Walnut Canyon Alluvium | Alluvial deposits in Walnut Canyon with high (primary) permeability. Porous media flow, rapid infiltration and lateral interflow. | 0 - 7 m (0 - 20 ft) | 0.25 - 0.50 ²⁾ | $0.3 \cdot 10^1 - 0.3 \cdot 10^3$ ($1.0 \cdot 10^1 - 1.0 \cdot 10^3$) ²⁾ |
| Tansill Dolomite and Siltstone | Thinly bedded, dolomitized limestone, interbedded with laterally discontinuous siltstones. Subcutaneous zone present. Vertical microfracture flow and locally lateral movement at bedding planes. | 2.5 - 7 m (8 - 20 ft) [0 - 1 m] [(0 - 3 ft)] | 0.02 ³⁾ [0.35 - 0.50] ²⁾ | $0.3 \cdot 10^{-5} - 0.3 \cdot 10^{-3}$ ($1.0 \cdot 10^{-5} - 1.0 \cdot 10^{-3}$) ³⁾ [$0.3 \cdot 10^{-2} - 0.3$] [($1.0 \cdot 10^{-2} - 1.0$)] ²⁾ |
| Yates Siltstone | Extensive, continuous siltstone beds of fine grained quartz and detrital fragments. Low permeability. Significant lateral flow along lithologic contacts. | 0 - 0.3 m (0 - 1 ft) | | $0.3 \cdot 10^{-2} - 0.3$ ($1.0 \cdot 10^{-2} - 1.0$) ²⁾ |
| Yates Sandstone and Dolomite | Competent, thinly bedded dolomite interbedded with sandstone and siltstone layers. Some porous media flow, primarily in the sandstone; significant microfracture flow; some (local) flow along facies contacts. | 10 - 40 m (30 - 120 ft) | 0.005 ³⁾ | $1.7 \cdot 10^{-5}$ ($5.0 \cdot 10^{-5}$) ³⁾ |
| Seven Rivers Dolomite | Thinly bedded, fine grained dolomite. Thin sandstone stringers are intercalated with the dolomite and wedge out as they approach the reef. Microfracture flow and some (local) flow along facies contacts. | 110 - 200 m (335 - 600 ft) | | |
| Massive Capitan Limestone | Permian reef structure with vugs filled with secondary calcite crystallization. This unit is highly fractured and cavernous. Primarily vertical, micro- and macrofracture flow. Convective vapor-phase flow in caves. | 250 - 335 m (750 - 1000 ft) | 0.015 - 0.020 ³⁾ | $1.2 \cdot 10^{-2}$ ($3.5 \cdot 10^{-2}$) ³⁾ |
| Foreslope Capitan Limestone | Foreslope member of Permian reef. Talus slope on basinward edge of reef, dipping at angles of 30 degrees or more. Reef prograded basinward over talus. Vertical microfracture flow; (local) lateral flow along bedding planes. | 250 - 335 m (750 - 1000 ft) | | |

1) Numbers between brackets denote values for Siltstone Member of Tansill Formation.

2) Values taken from Fetter (1994).

3) Values taken from Hill (Table 12, 1987).

immediately below the Yates Siltstone, is a series of sandstones interbedded with dolomite. The Seven Rivers Dolomite is mostly a dolomitic unit similar to the dolomite of Yates Sandstone and Dolomite. It does not crop out in the study area. The presence of the persistent sandstone and siltstone layers distinguishes the Yates from the dolomitic Tansill Formation and Seven Rivers.

The Yates Formation and Seven Rivers Formation are somewhat karstic backreef units with fine-grained interlayers of low permeability. The Massive Capitan Limestone hydrogeologic unit developed diagonally between the previously mentioned hydrogeologic units and the Foreslope Capitan Limestone because the reef prograded throughout Permian time (Figure 4). Finally, the Foreslope Capitan Limestone is a foreslope deposit consisting of poorly bedded breccia and slope deposits. Four hydrogeologic cross-sections have been prepared to illustrate the hydrostratigraphy and hydrologic system domains discussed later in this section (Figures 20, 21, 22 and 23; Figure 19 shows the location of these cross-sections).

From site observations (Brooke, 1996) and previous field work (Hill, 1987), it is concluded that much of the hydrogeologic system displays low primary porosity characteristics with flow channeled through fractures and solution channels. Typical primary porosity values range between 0.005 for the Yates Dolomite and Sandstone, 0.015 for the Massive Capitan Limestone, 0.02 for the Tansill Dolomite, and 0.4 for the Tansill Siltstone (Hill, 1987). The primary permeability for these formations ranges from $0.3 \cdot 10^{-3}$ - $0.3 \cdot 10^{-5}$ m/d ($1.0 \cdot 10^{-3}$ - $1.0 \cdot 10^{-5}$ ft/d) for the Tansill Dolomite and $1.7 \cdot 10^{-5}$ m/d ($5.0 \cdot 10^{-5}$ ft/d) for the Yates Sandstone and Dolomite, to $1.2 \cdot 10^{-2}$ m/d ($3.5 \cdot 10^{-2}$ ft/d) for the Massive Capitan Limestone (Hill, 1987). Primary permeability of siltstones is reported to range from $0.3 \cdot 10^{-2}$ to 0.3 m/d ($1.0 \cdot 10^{-2}$ to 1.0 ft/d) (Fetter, 1994).

Subsurface Flow

Water occurs in the caverns in two dominant forms: 1) drips (primarily from stalactites and soda straws) onto flowstone and stalagmites and into pools, and 2) pools (from drips or other sources). During site visits, cave features were characterized for hydrologic purposes as either wet (events occurring today) or dry (water influx in the past was noted

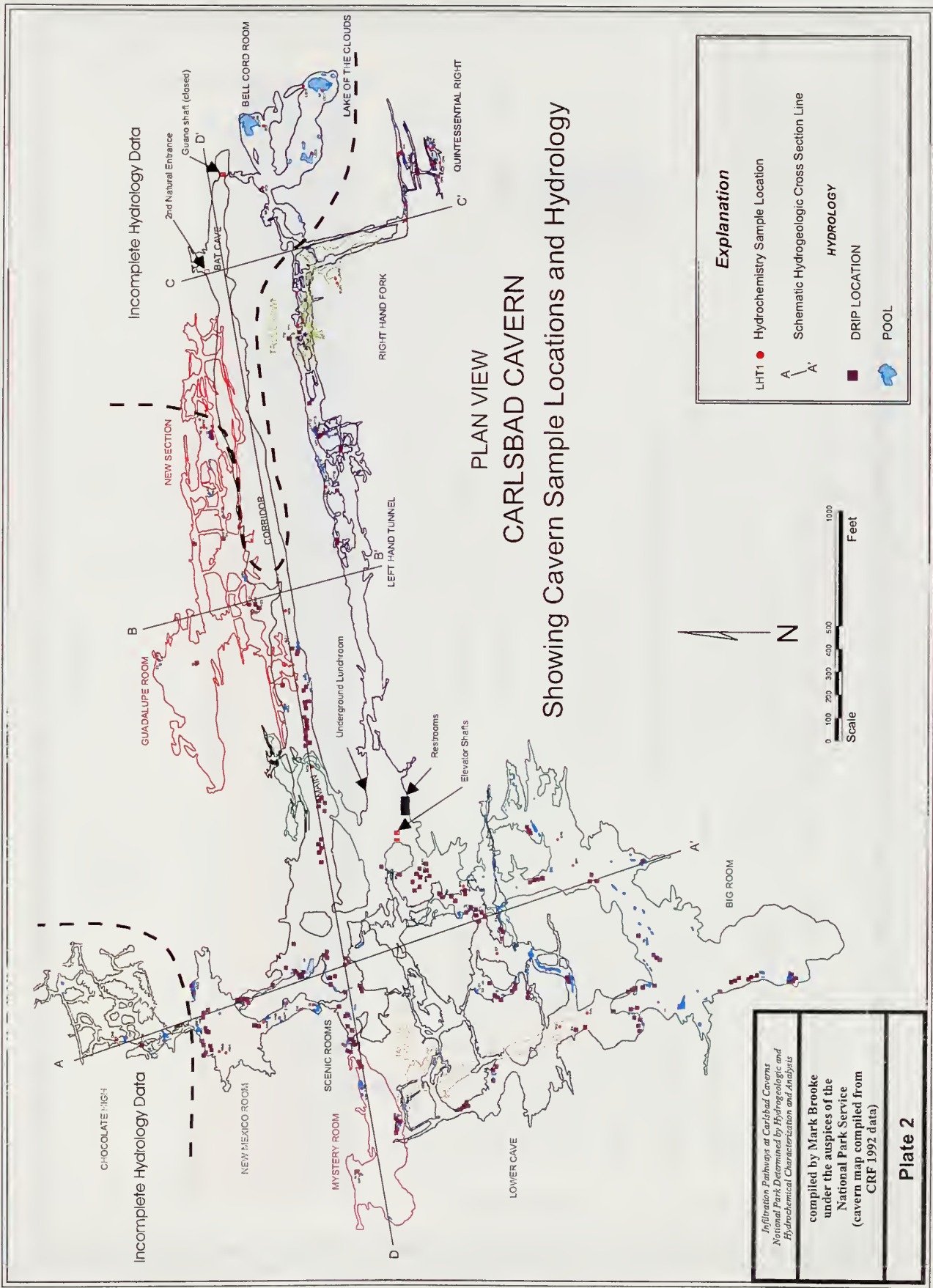
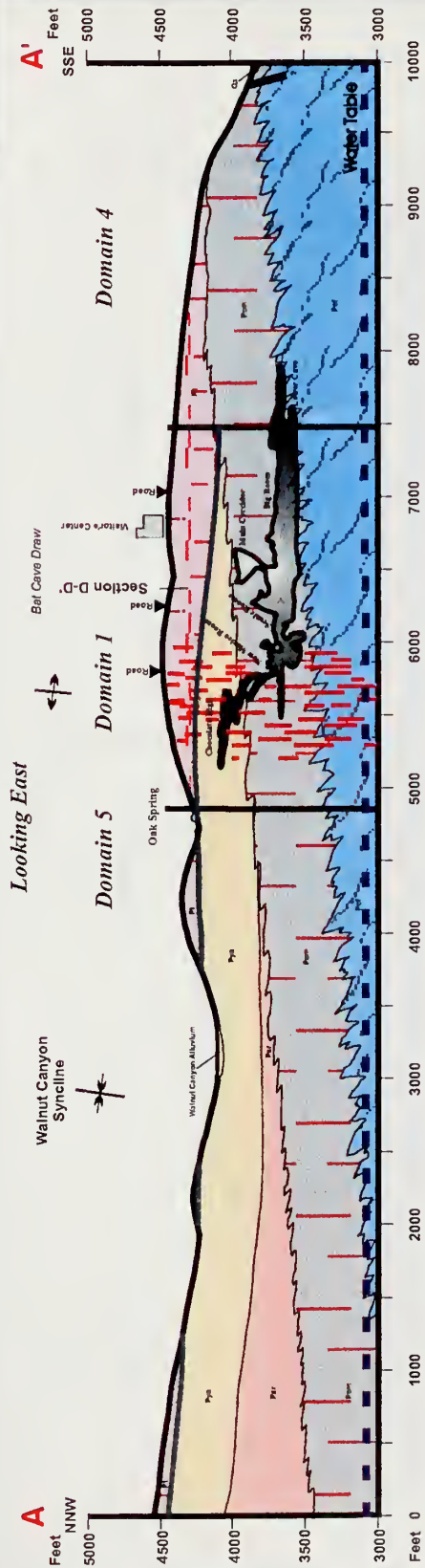


Figure 19. Plan view of Carlsbad Cavern area with cavern layout, locations of drips, pools and sampling points, and the location of the hydrogeologic cross-sections (from Brooke, 1996).



CARLSBAD CAVERN SCHEMATIC HYDROGEOLOGY SECTION A-A' (section trends parallel to Domain 2)

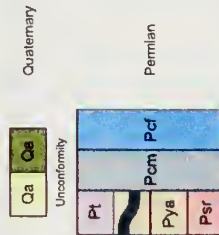
Description of Map Units

- Qa** Quaternary Delaware Basin Alluvium
- Qa** Quaternary Walnut Canyon Alluvium
- Pt** Permian Tansil Dolomite and Siltstone - thinly bedded with discontinuous vertical joints
- Pya** Permian Yates Siltstone - bed of fine grained quartz and detrital fragments
- Psr** Permian Seven Rivers Dolomite - thinly bedded dolomite
- Pch** Permian Massive Capitan Limestone - reef limestone with continuous vertical joints on spacing of 25 to 100 feet
- Rf** Permian Foreslope Capitan Limestone - beds dipping up to 35 degrees to the southeast

Explanation of Map Units

- Macro-fracture associated with regional structure**
- Syncline**
- Anticline**
- Barrera Fault (approximate location and estimated dip)**
- Contact**

Correlation of Map Units



Description of Hydrogeologic Domains

- Domain 1** Infiltration occurs along bedding planes and hydrogeologic contacts with minor structural control
- Domain 4** Minimal infiltration occurring in minor structure southeast of Yates Siltstone Member
- Domain 5** Minimal infiltration occurring in backreef facies along bedding and joints and no infiltrate entering the cavern

Infiltration Pathways at Carlsbad Cavern
National Park, New Mexico
Hydrogeologic Characterization and Analysis

compiled by Mark Brooke
under the auspices of the
National Park Service
(cavern map compiled from
CRF 1992 data)

Plate 4

Figure 20. Carlsbad Cavern hydrogeologic cross-section A-A' (from Brooke, 1996).

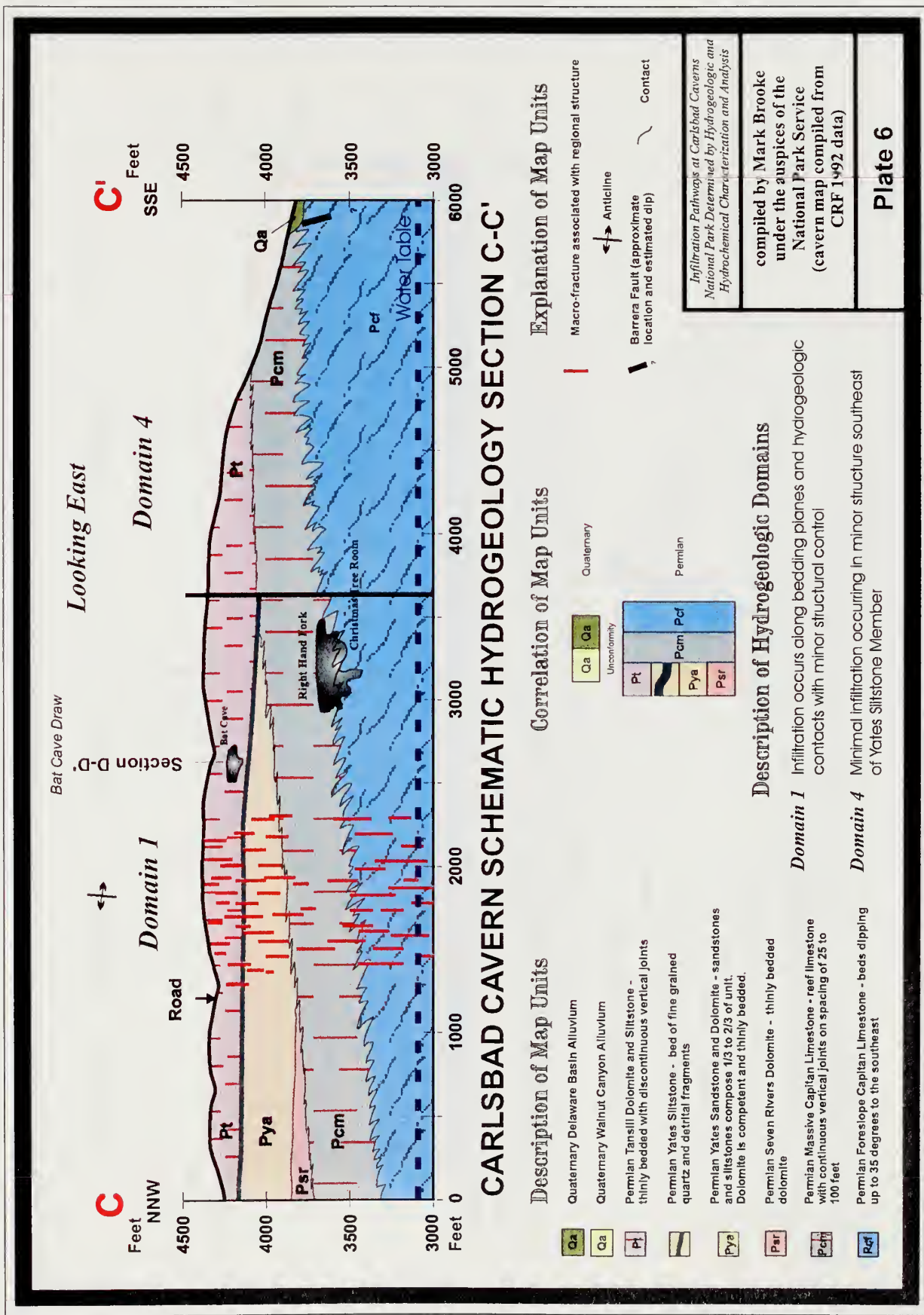
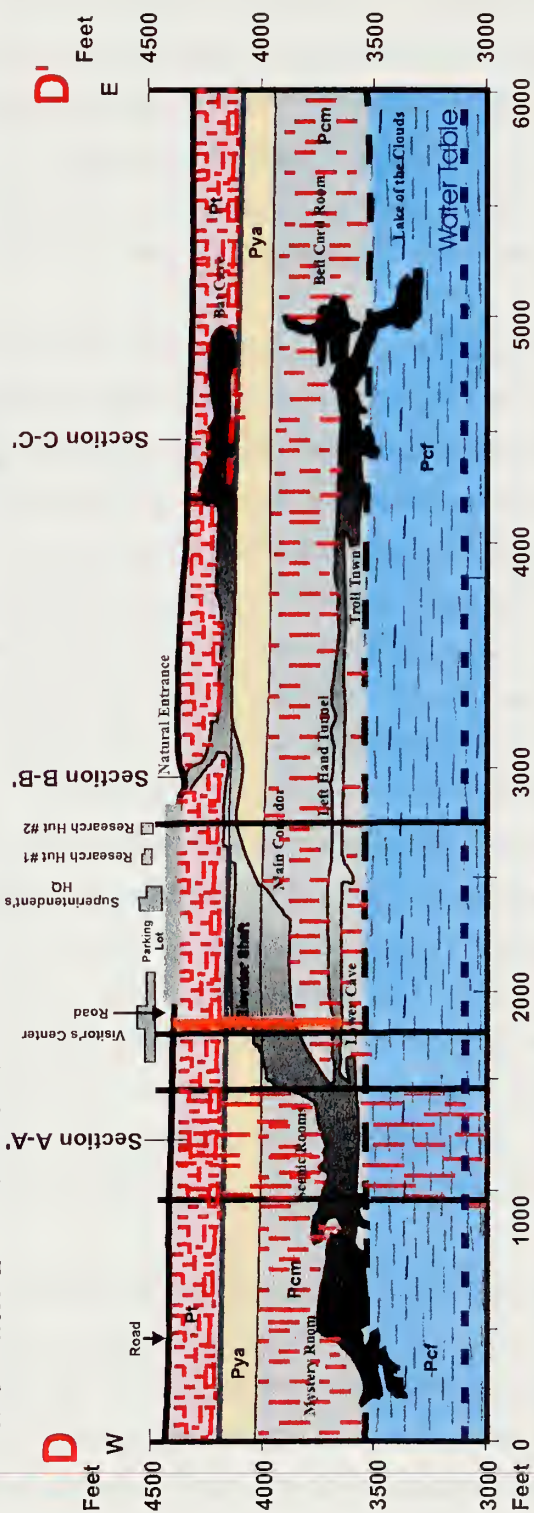


Figure 22. Carlsbad Cavern hydrogeologic cross-section C-C' (from Brooke, 1996).

Domain 1 Domain 2 Domain 3 Looking North



CARLSBAD CAVERN SCHEMATIC HYDROGEOLOGY SECTION D-D' with Left Hand Tunnel projected onto section D-D'

Explanation of Map Units

Macro-fracture associated with regional structure

Contact located approximately within 100 feet

Description of Map Units

Permian Tansill Dolomite and Siltstone - thinly bedded with discontinuous vertical joints

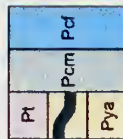
Permian Yates Siltstone - bed of fine grained quartz and detrital fragments

Permian Yates Sandstone and Dolomite - sandstones and siltstones compose 1/3 to 2/3 of unit. Dolomite is competent and thinly bedded.

Permian Massive Capitan Limestone - reef limestone with continuous vertical joints on spacing of 25 to 100 feet

Permian Foreslope Capitan Limestone - beds dipping up to 35 degrees to the southeast

Correlation of Map Units



Permian

Description of Hydrogeologic Domains

Domain 1 Infiltration occurs along bedding planes and hydrogeologic contacts with minor structural control

Domain 2 Increased permeability due to New Mexico Room fracture set

Domain 3 Cavern intersects Yates Siltstone Member allowing increased infiltration into the cavern and units below

Infiltration Pathways at Carlsbad Caverns
National Park Determined by Hydrogeologic and
Hydrochemical Characterization and Analysis

compiled by Mark Brooke
under the auspices of the
National Park Service
(cavern map compiled from
CRF 1992 data)

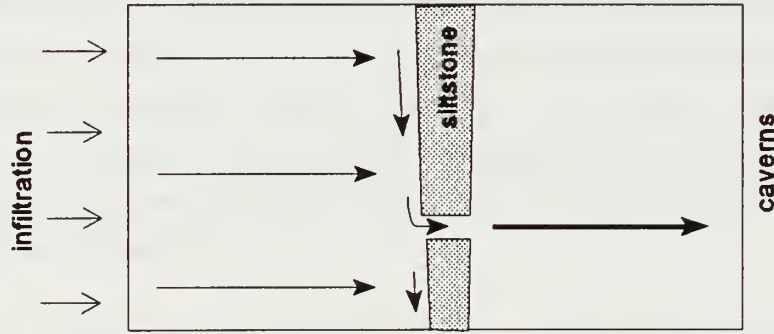
Plate 7

Figure 23. Carlsbad Cavern hydrogeologic cross-section D-D' (from Brooke, 1996).

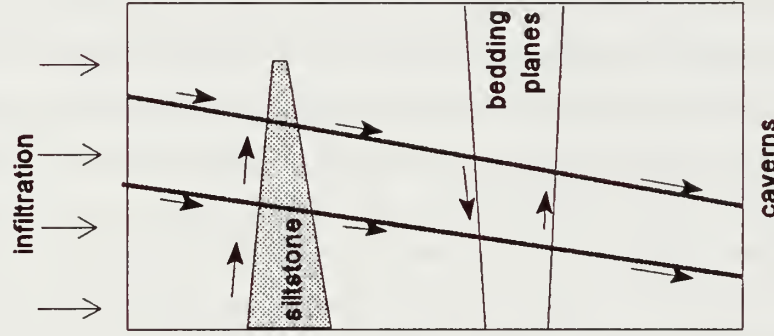
in some areas, but water activity is limited or non-existent today). The distribution of these features with respect to fractures, facies contacts, and within facies has been characterized and mapped in terms of hydrostratigraphy (Brooke, 1996). Drips and pools occur in localized areas. Pools have a rather long residence time (Ingraham et al., 1990). Excess water disappears in the cave floor and eventually joins the regional ground-water system as recharge. Drip rates are rather variable, but essentially continuous resulting in rather small flow rates, as expected for such an arid system.

The movement of water in the subsurface of Carlsbad Cavern is considered a dual porosity process with flow occurring in rock pores and well-connected microfractures (diffuse flow), and through fractures and dissolution channels (conduit or piston flow). Several pathways exist for the movement of water through the fractured and karstic rock layers at Carlsbad Cavern. The prevalent pathways in a particular zone are determined by the local and regional geology, hydrology, hydrogeology, soils and climate. Possible pathways for in water dissolved chemicals include (Figure 24): 1) macrofractures connecting the (near-) surface directly with the caves; 2) well-connected microfracture systems; 3) horizontal fractures and bedding planes; 4) solution channels; 5) the elevator shaft; and 6) cave entrances. Specifically, locations where fractures cross may provide a rapid pathway downwards, often enhanced by preferential dissolution. Some of the larger fractures and fracture zones are visible at the surface as lineaments and fracture traces, as well as in the cavern in the form of a linear series of corridors and halls (e.g., Talcum Passage/Left Hand Tunnel, and Big Room/New Section/Chocolate High). Well-connected microfractures are found underneath the top of ridges and the center of depressions due to the effects of stress and strain related to local and regional rock movement and deformation. Furthermore, within the caves, drips, surface flow and vapor transport contribute to the movement of water and dissolved chemicals.

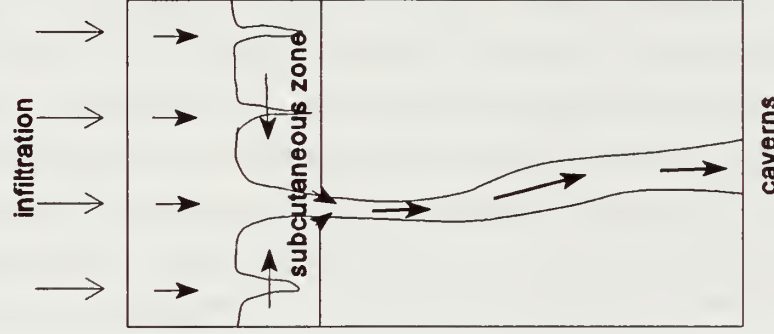
Effects of precipitation travel through the subsurface in two forms: 1) a pressure pulse resulting in increased pore velocities and drip rates across the profile shortly after the pulse is initiated; and 2) a mass-transport pulse representing the actual movement of water and dissolved chemicals through the profile from the surface to the caves and the regional ground-water system. From site observations (Brooke, 1996) and previous field work (Hill, 1987) it is concluded that much of the limestone system displays low primary porosity



a. diffuse flow through well-connected microfractures in upper layers; lateral movement along siltstone till joints in siltstone are reached; local percolation in fracture network beneath siltstone.



b. pathway through macrofractures; some lateral movement along bedding planes and siltstone toward edge of siltstone.



c. pathway along walls of solution channels (sheet flow); potential turbulent flow if enough water available. Note lateral flow in subcutaneous zone.

Figure 26. Generalized pathways for dissolved contaminants in the Carlsbad Cavern system.

characteristics with flow channeled through (macro- and micro-) fractures, weathered bedding planes and lithological contacts, and solution channels. Based on isotope studies performed in Carlsbad Cavern, Chapman et al. (1992) concluded that most flow takes place as seepage flow through interconnected pores and microfractures and not as piston flow through major fractures. Hill (1987) determined that in the upper cavern area, within the Tansill and Yates Formations, the flow is dominated by vertical joints and dipping bedding planes and that the underlying Capitan Reef is characterized by diffuse flow due to the absence of bedding planes and increased porosity. Some areas provide an exception, notably Green Lake, where the isotope composition indicates that recharge takes place by rapid conduit flow from the surface (Chapman et al., 1992). This location is also characterized by rapid pressure response to rainfall (Williams, 1983).

Locally, zones of high saturation or even full saturation (perched water) occur, often above low-permeability, fine-grained interbeds and formation contacts. Such perched zones have been observed in the elevator shafts and at the surface near seeps (in Walnut Canyon and on the ridge top along Walnut Canyon Desert Drive), among others (Brooke, 1996). It appears that at different elevations significant horizontal flow occurs, probably caused by perching at formation contacts and interbedded siltstone layers. The location of springs (e.g., Oak Spring), seeps and evaporative vegetation on top of the ridge and along its slopes indicate a significant discharge of infiltrated water high in the ridge profile (Figure 9). Chapman et al. (1992) hypothesized that the perched zones in the Carlsbad Cavern area are rather local, causing some modification of vertical flow paths. They specifically referred to the role of the subcutaneous zone described by Williams (1983). However, Brooke (1996) concluded that due to the extent and continuity of the Yates Siltstone, significant lateral diversion takes place at the contact of the Yates and the Tansill. Ingraham et al. (1990) suggested that the presence of pools in the caves also signify local perched zones which gain water from drips and lose water primarily through downward leakage.

The presence of a subcutaneous zone near the surface at Carlsbad Cavern has a significant influence on the local vadose zone hydrology. A subcutaneous zone is the upper weathered layer of rock in the unsaturated zone, directly beneath the soil zone (Williams, 1983). It often has a high secondary permeability, arising from chemical

solution. This permeability decreases with depth and may be further reduced when the solution channels have been filled in with low permeable material. The high permeability at the top of this zone allows for rapid infiltration of precipitation. However, with depth decreasing permeability does not allow rapid downward percolation, except where open joints or fractures connect with deeper layers. Thus, the subcutaneous zone acts as a reservoir, particularly after storms. Intense storms may lead to saturation or near-saturation conditions in this zone, which in turn may lead to lateral flow towards points of rapid vertical percolation (Williams, 1983).

In the study area, soils are absent, very thin or restricted to solution channels at the surface. The weathered top of the Tansill Formation is exposed at the surface, forming a subcutaneous zone of a few feet thick on top of the ridge and in the depressions (McLean, 1996; pers. comm.). Most of the precipitation generated by low to moderately intense storms infiltrates into this zone and runs off as interflow or throughflow towards Bat Cave Draw, Walnut Canyon, and the Delaware Basin. A relatively small amount percolates towards the caves and the regional water table. Due to the limited storage capacity of the subcutaneous zone, intense storms typically fill up this reservoir resulting in (infiltration excess or Hortonian) overland flow, as observed during the study.

Williams (1983) suggested that there is a large amount of water in storage in the unsaturated zone at Carlsbad Cavern, particularly in the subcutaneous zone. He postulated a capillary barrier at the base of the subcutaneous storage zone, regulating percolation into the deeper vadose zone, as an explanation for the lack of significant pulse effects after rainfall. However, the low permeability of the lower part of the subcutaneous zone itself limits the infiltration capacity of that zone, without a capillary barrier necessarily being present. Furthermore, Brooke (1996) argued that rather continuous siltstone layers in the Tansill and especially the Yates Formation are more likely to provide the basis of such a large storage reservoir.

The results of the study by Chapman et al. (1992) indicate that isotopic homogenization of individual and seasonal precipitation events take place high in the profile. This is apparently due to the presence of complex, well-connected, dense fracture patterns and subsequent flow paths, as well as to pulse-damping and water-mixing in perched

reservoirs near the surface. It is believed that such fracture networks are common in the Tansill and Yates Formations (Hill, 1987; Chapman et al., 1992). However, the Massive Capitan Limestone does not seem to contain such well-developed fracture networks. From the distribution of pools and drips it is clear that pathways through this formation are more localized. The wide-spread presence of speleothems are more indicative of prehistoric hydrology than present-time hydrology.

Chapman et al. (1992) noted that heavy-isotope enrichment may occur while cave drip water is temporarily stored in zones of saturation or near-saturation above drip entry points into the cavern. Large openings (e.g., caves) act as (capillary) barriers to infiltration and near-saturation conditions may be required to generate enough pressure-head to overcome surface tension forces (i.e., capillary forces) and drip into the cave. This phenomenon may divert water to nearby joints where it finds an easier way out into the cave. Such joints may be directly related to local stress release in the cave walls as a result of cave forming.

Williams (1983) studied the correlation between rain events, drip rates and pool levels using data collected by McLean (1977). Drip rates reflect the arrival of pressure pulses following a precipitation event. Pool level responses typically lag precipitation by 6 to 14 weeks. They are smoother than individual drip rates and reflect the joint influence of various drips with highly varying discharge rates. Correlated drip lags were only found for Bat Cave (2 weeks; about 60 m [180 ft] below the land surface) and Green Lake (five weeks; about 250 m [750 ft] below the surface). Williams (1983) concluded that percolation routes are highly variable and often independent from each other. Many drips showed little variation in point discharge due to the damping effect of small, tortuous pathways. Hill (1987) reported travel times for the pressure pulse ranging from a few hours to a few weeks.

Based on their isotope work, Chapman et al. (1992) reported average flow rates from the surface to Lower Cave and Lake of the Clouds, about 265 m (800 ft) below the surface, ranging from less than 7 to more than 16 m/year (20 - 50 ft/year). These seepage velocities represent travel times (that is, residence times) between the surface and the lower cave level of 15 to 35 years. Recently, the results of a tritium study in Lechuguilla

Cave (Turin and Plummer, 1995) indicated that for the top 300 m (900 ft), a travel time of 20 to 50 years is normal. This study also showed a wide scatter in residence times at shallow depths, indicative of complex, fracture-dominated flow. Although the hydrogeology of the Lechuguilla Cave is significantly different from that of Carlsbad Cavern, the recharge velocities found for Lechuguilla Cave are of the same order of magnitude as those present at Carlsbad Cavern. Furthermore, it can be expected that at shallow depths at Carlsbad Cavern, the same wide scatter in residence times can be found.

Hydrologic System Domains

The study shows that the Carlsbad Cavern area can be divided in five hydrologic system domains (Figure 25; Table 3; see also the cross-sections in Figures 20, 21, 22 and 23). In turn, some of these domains can be divided in subdomains. A hydrologic system domain is defined as an area with distinct hydrologic behavior resulting from differences in topography, hydrogeology, hydrostructure, and hydrochemistry. The differentiation between domains depends on the purpose of the study. In this study, the delineation of the hydrologic domains is primarily aimed at assessing the caves vulnerability to contamination from the surface. Brooke (1996) describes the delineation of these domains in detail.

The first domain described by Brooke (1996) is characterized by the presence of the rather continuous Yates Siltstone hydrogeologic unit. Due to the low permeability of this unit and its areal extent, significant lateral flow occurs, controlled by its dip which is associated with the ridge anticline and the Cenozoic Guadalupe uplift. The hydrologic importance of this feature is corroborated by the presence of a line of springs, seeps and phreatophytes in Walnut Canyon and the increased presence of drips and pools in the caves at the southern facies contact. The rather continuous character of these springs and seeps, as well as the presence of vegetation that requires a more-or-less continuous water supply, is indicative for the significant perched storage present above this siltstone layer.

Permeability in domain one may have been enhanced in zones of open fractures at the top of the ridge parallel to the axis of the syncline. Among others, this may have led to

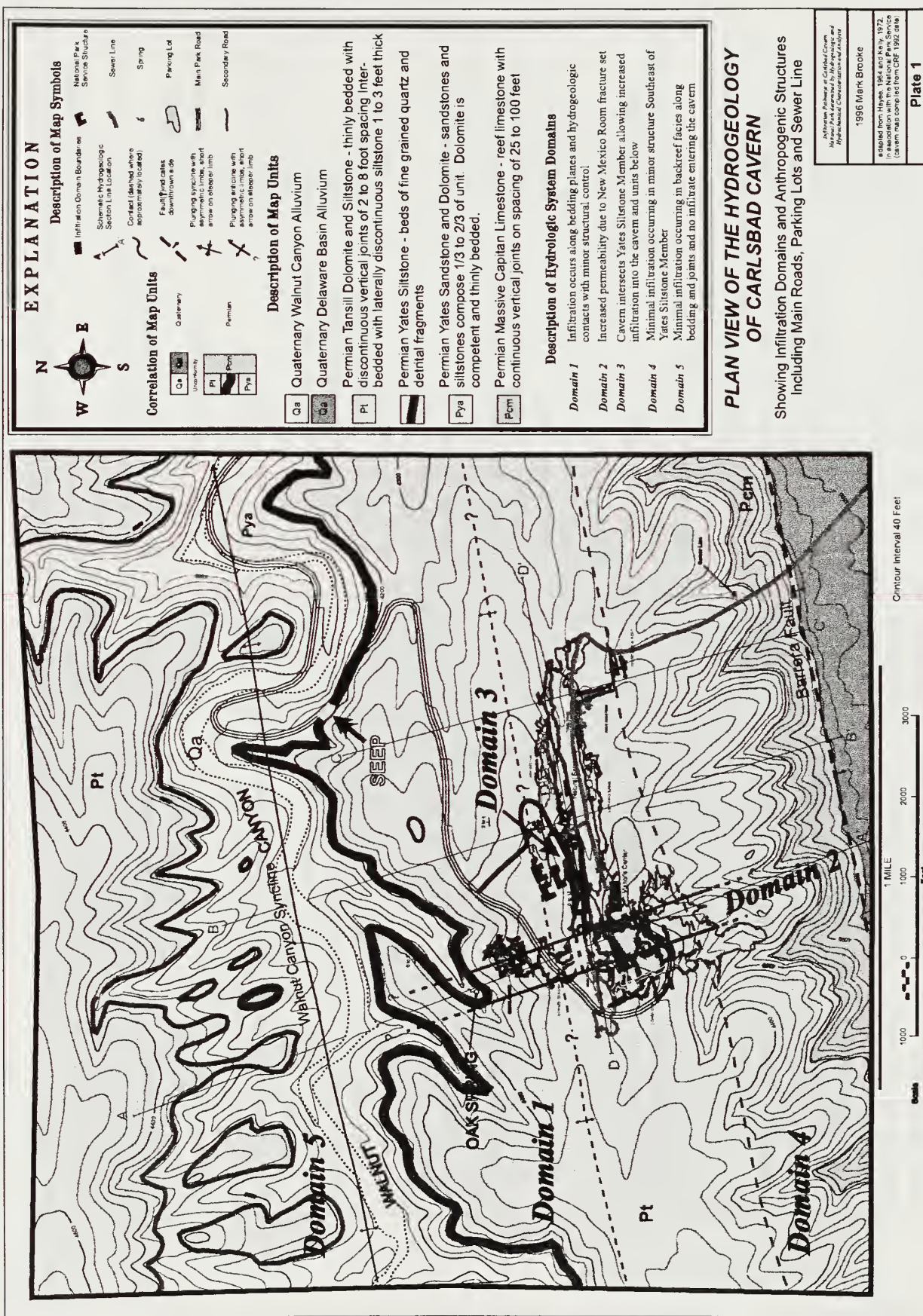


Table 3. Summary of hydrologic system domain characteristics (from Brooke, 1996).

| Domain | Infiltration Type and Distribution | Hydrologic Units Present (<i>major control in italics</i>) | Hydro-structure | Flow Mechanisms (<i>dominant mechanism in italics</i>) | Evidence for domain in system |
|--------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1 | Diffuse infiltration zones in highland areas with slopes ranging from 2% to 10%. Two areas of concave topography focus recharge during storm events. | <ul style="list-style-type: none"> Tansill Dolomite and Siltstone Yates Siltstone Yates Sandstone and Dolomite Massif Capitan Limestone Foreslope Capitan Limestone | Possible enhancement of permeability due to anticline | <ul style="list-style-type: none"> subcutaneous zone flow microfracture flow lateral flow along low-permeability interlayers <i>horizontal flow along lithologic contacts</i> <i>down-dip</i> vertical flow between facies contacts macrofracture flow | <ul style="list-style-type: none"> springline in Walnut Canyon drips in fractures oriented N80°E increased hydrologic activity at southern facies contact |
| 2 | Generally diffuse infiltration with small area of focused recharge in Bat Cave Draw and minimal infiltration occurring at ends of domain due to steep slopes (greater than 20%). | <ul style="list-style-type: none"> Tansill Dolomite and Siltstone Yates Siltstone Yates Sandstone and Dolomite Massif Capitan Limestone Foreslope Capitan Limestone | New Mexico Room fracture set trending N15°W | <ul style="list-style-type: none"> subcutaneous zone flow microfracture flow lateral flow along low-permeability interlayers <i>horizontal flow along lithologic contacts</i> <i>down-dip both within domain 2 and from domain 1 (flow concentration)</i> <i>macrofracture flow</i> | <ul style="list-style-type: none"> presence of pools and drips drips in fractures oriented N15°W Oak Spring (flow concentration) |
| 3 | Focused recharge due to concave topography, but parking lot may inhibit direct infiltration. | <ul style="list-style-type: none"> Tansill Dolomite and Siltstone <i>Yates Siltstone absent</i> Yates Sandstone and Dolomite Massif Capitan Limestone Foreslope Capitan Limestone | none | <ul style="list-style-type: none"> subcutaneous zone flow <i>microfracture flow</i> lateral flow along low-permeability interlayers <i>seepage (from domain 1) into cavern at Yates Siltstone contact</i> vertical flow between facies contacts macrofracture flow | <ul style="list-style-type: none"> presence of pools and drips due to breach in Yates Siltstone increased speleothem development walls seep at contact |
| 4 | Minimal infiltration curing due to steep slopes along front of escarpment. | <ul style="list-style-type: none"> Tansill Dolomite and Siltstone <i>Yates Siltstone absent</i> Massif Capitan Limestone Foreslope Capitan Limestone | none | <ul style="list-style-type: none"> <i>vertical microfracture flow</i> <i>vertical macrofracture flow</i> lateral flow along Yates Siltstone from domain 1 into domain 4 where it moves downward in the absence of siltstone | <ul style="list-style-type: none"> minimal hydrologic response in Bottomless Pit area increased hydrologic activity at facies contact |
| 5 | Generally minimal infiltration due to steep slopes in Walnut Canyon with the exception of focused recharge curing at the canyon bottom. Also, some water reenters system beneath spring/seep line. | <ul style="list-style-type: none"> <i>Tansill Dolomite and Siltstone discontinuous</i> <i>Yates Siltstone discontinuous</i> Yates Sandstone and Dolomite Seven Rivers Dolomite Massif Capitan Limestone Foreslope Capitan Limestone Walnut Canyon Alluvium | Effect of Walnut Canyon Syncline hydro-structure not determined | <ul style="list-style-type: none"> <i>lateral porous media flow (in Alluvium)</i> <i>vertical microfracture flow (in Perm)</i> lateral flow along low-permeability interlayers microfracture flow | <ul style="list-style-type: none"> no evidence for this domain within cave complex decreasing flow rate downstream during creek runoff |

increased erosion resulting in the depression of Bat Cave Draw. However, the lateral diversion at the siltstone layers mask any proof of enhanced vertical permeability. Locally, the siltstone layer may be somewhat fractured to the extent that some water finds a path into the underlying formations and into the caves. In the formation above and beneath the Yates Siltstone, flow takes place through well-connected microfractures and along bedding planes. Domain one contains an extensive subcutaneous zone, especially in the uplands, damping variations in infiltration rate and redistributing infiltrated water.

Within domain one, three subdomains are recognized based on type of surface infiltration (Figure 9). The surface infiltration in most of the area is diffuse as it consists primarily of highlands with slope of 2% to 10%. Focused infiltration occurs in areas of concave topography like Bat Cave Draw. Steep slopes with little or no infiltration are also present in this domain.

The second domain, described by Brooke (1996), is contained within domain one and is characterized by the New Mexico Room fracture set trending N15°W enhancing vertical percolation, including through the Yates Siltstone present in this area. The fracture set that defines domain two allow the enhanced percolation through well-connected microfractures as well as through macrofractures and solution channels. This enhanced percolation is responsible for the numerous drips and pools from Chocolate High through the Scenic Rooms to the Crystal Springs Dome area of the Big Room (see section A-A' of Figure 19). Due to the presence of these active fractures, pressure pulse response times are short (about five weeks at a drip in the Scenic Rooms). Domain two has a significant subcutaneous zone. As is the case for domain one, the surface infiltration type and distribution within this domain is generally diffuse except for focused infiltration occurring within Bat Cave Draw.

Domain two receives a significant portion of its percolation from domain one. Flow moves from the west down dip along the Yates Siltstone unit, that characterizes domain one, until it reaches the fracture zones in the Tansill, Yates, and Capitan hydrogeologic units of domain two, where it percolates downwards. The Yates Siltstone within domain two is, to some extent broken up by these fractures, but still controls significant lateral flow northward to Oak Spring and eastward to domain three.

The third domain is according to Brooke (1996) defined by water moving down dip along the Yates Siltstone to the southeast until it is intercepted by the Main Corridor of Carlsbad Cavern between Devil's Spring and Iceberg Rock. The Yates Siltstone is absent within this area of the cavern and water either percolates directly as microfracture flow from the surface through the Tansill Dolomite and Siltstone unit and the Yates Sandstone and Dolomite unit, or migrates from areas northwest of this domain along the Yates Siltstone into the Main Corridor of the cavern, between Devil's Spring and Iceberg Rock. The latter mechanism causes the wall seeps present at the Yates Siltstone contact. Drips and pools in this area result from the direct hydraulic contact between the Tansill Formation and the units underlying the Yates Siltstone. Vertical flow takes place primarily through well-connected microfractures. Surface infiltration type and distribution is focused due to the concave topography. Domain three is contained entirely within domain one.

The fourth hydrologic domain recognized by Brooke (1996) is characterized by the facies pinchout of the Yates Siltstone along the reef. The Tansill hydrogeologic unit and the Massive Capitan Limestone control the infiltration within this domain. Minimal infiltration occurs from the surface due to the steep slopes along the margin of the escarpment. Water from domain one infiltrates along the facies boundary between the backreef and reef where the Yates Siltstone pinches out against the Massive Capitan Limestone. This pinchout provides a significant source of water at this facies transition (see for example Quintessential Right and Cave Man Junction area of the Big Room). From this location, water is hypothesized to migrate almost vertically through the fracture network of the Massive Capitan Limestone.

Finally, the fifth domain is characterized by water moving northwest to the north of the axis of the anticline structure (Brooke, 1996). Water infiltrates into backreef units beyond the northern boundary of the Yates Siltstone and does not intersect the known extent of the cavern. This domain is affected by rapid surface runoff because slopes are steep in this area. Focused recharge can occur at the bottom of Walnut Canyon when excess precipitation fills the stream channel of Walnut Creek. In the Alluvium at the canyon bottom, lateral porous medium flow may continue for some time after the surface runoff has stopped due to the low permeability and maximum infiltration rates of the underlying Yates Formation.

At the boundary between domain one and domain five, water leaves the subsurface at the spring line formed by the contact of the Yates Siltstone unit with the slope and reenters the subsurface beyond this spring line. From this location, water can continue within the backreef facies below the siltstone unit. However, this water does not enter the cavern system and ultimately may provide recharge to the regional ground-water system.

Contaminant Pathways

At the surface, the subcutaneous zone infiltration mechanism allows water to enter through fractures at the surface that close at depth. The water gradually becomes homogenized and moves laterally until it is intercepted by a master joint within the Tansill hydrogeologic unit. Vadose flow mechanisms within the Tansill, Yates, and Seven Rivers hydrogeologic units include a microfracture network within the competent dolomitic hydrogeologic units, and lateral flow along hydrogeologic units of lesser permeability and competency. Macrofracture flow mechanisms may dominate in the immediate vicinity of the ridge anticline mapped by Kelly (1971). This may enhance flow through and between these different backreef hydrogeologic units. There is also a fracture set trending N15°W, the New Mexico Room fracture set, that allows the macrofracture vadose flow mechanism to dominate in the vicinity of the fracture set. Evidence for enhanced permeability due to this macrofracture set includes the enhanced speleothem and drip activity occurring within this region. The extent of the speleothem development in this area of the New Mexico Room fracture set is unique within Carlsbad Cavern.

Infiltration of water into the Massive Capitan Limestone hydrogeologic unit is controlled by two vadose flow mechanisms. The backreef-reef facies contact controls the lateral distribution of water to this unit, and southeast of this facies transition, microfractures in the Tansill hydrogeologic unit transport water directly to the Massive Capitan Limestone. Within the reef, large, continuous macrofractures control the migration of water within this system. Most of the wet fractures within this zone trend N80°E (Figure 14). These fractures also allow water to infiltrate into the foreslope facies where bedding planes allow water to move laterally towards the Delaware Basin. The results of the hydrogeologic framework analysis indicate that flow within these different hydrogeologic units can be defined by the local structure and Permian reef geometry.

The hydrochemistry results obtained by Brooke (1996) provide a strong indication that at certain locations in the cavern, water quality is influenced by anthropogenic activities at the surface. Specifically, aluminum, zinc, total organic carbon (TOC), and nitrate show spatial distributions that can be explained using pathway analysis based on the presence of potential sources at the surface and the characteristics and extent of the various hydrologic system domains.

Brooke (1996) noted that the observed distribution of aluminum concentrations greater than 50 ppm (highest 10%) was limited to a few areas in the western portions of the cavern and in the extreme southeast of the cavern. These areas are near the main road to the visitor's center close to Bat Cave Draw and beneath southeastern segment of the sewer line. Because surface runoff from the parking lots and the maintenance yard contains high amounts of aluminum, Brooke (1996) suggested that the main road runoff also contains high aluminum. He hypothesized that water from the main road, parking lots and sewer line locations enters the focused infiltration area of Bat Cave Draw (Figure 9) where it mixes with water from other areas and enters the vadose system. Once in the Tansill hydrogeologic unit, water with elevated aluminum concentrations migrate downward until they intersect the Yates Siltstone (Figure 26). Depending on where these waters enters the Tansill, the flow patterns are different. Infiltrating runoff from the main road intersects the Yates Siltstone slightly north of Bat Cave Draw. From here (hydrologic domain two), these waters continue vertically through a network of open fractures to the New Mexico and Mystery Room below. Parking lot runoff enters the subsurface in Bat Cave Draw and intersects the Yates Siltstone east of hydrologic domain two, where it moves laterally down dip along the siltstone to the southeast and east. Along this path, aluminum enriched water either migrates downward through locals microfracture systems, or moves on until it encounters the facies change between the backreef and the massive reef where various fractures and solution channels provide paths towards the lower cavern elevations, and ultimately towards the regional water table. Brooke (1996) suggested that the elevated aluminum level in Lower Cave is caused by limited lateral flow and rapid capture by a microfracture network (Figure 26).

Relative high zinc concentrations (top quartile greater than 20 ppb) were detected in the Big Room, Lower Cave, the Main Corridor, and the Quintessential Right and are

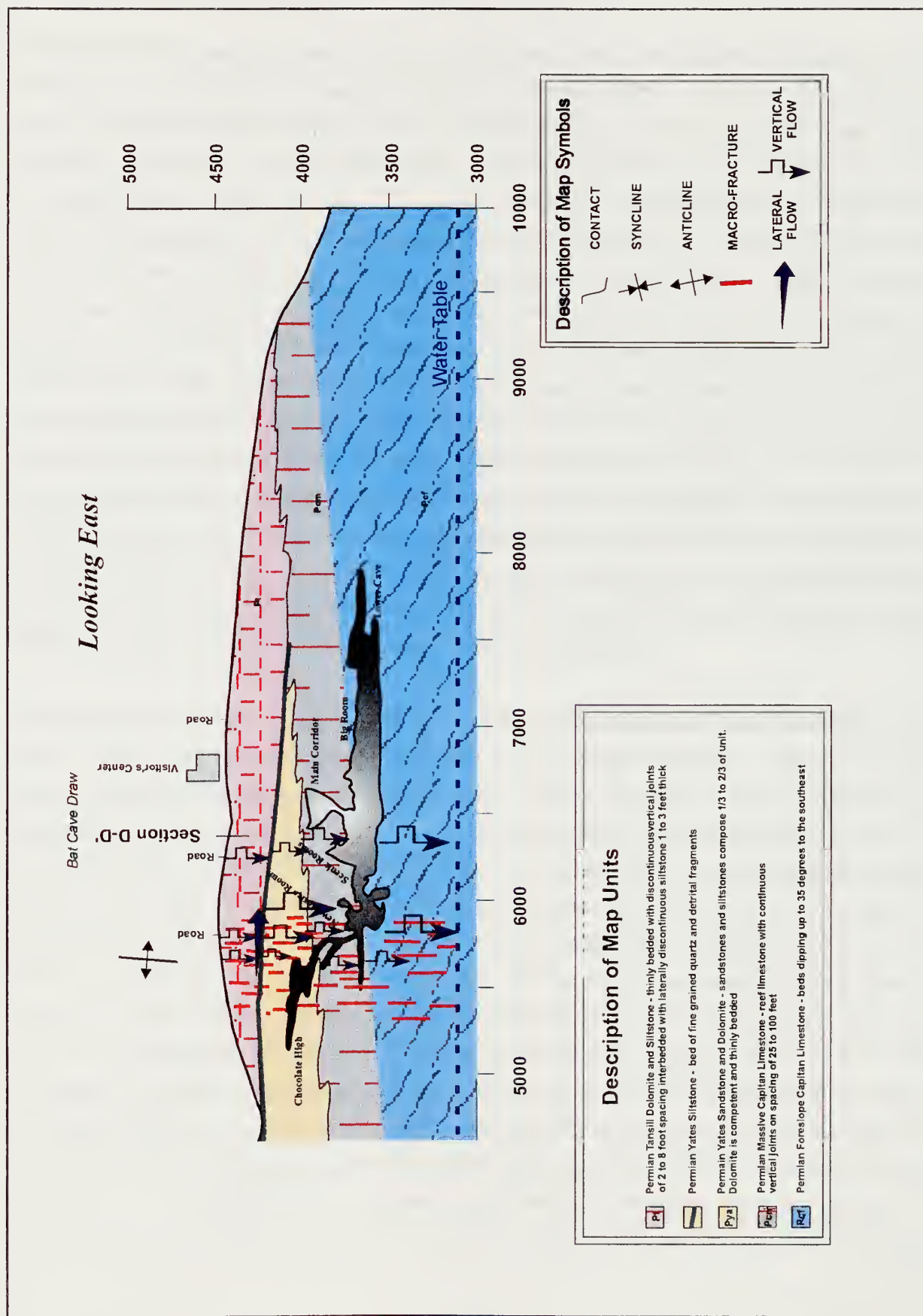


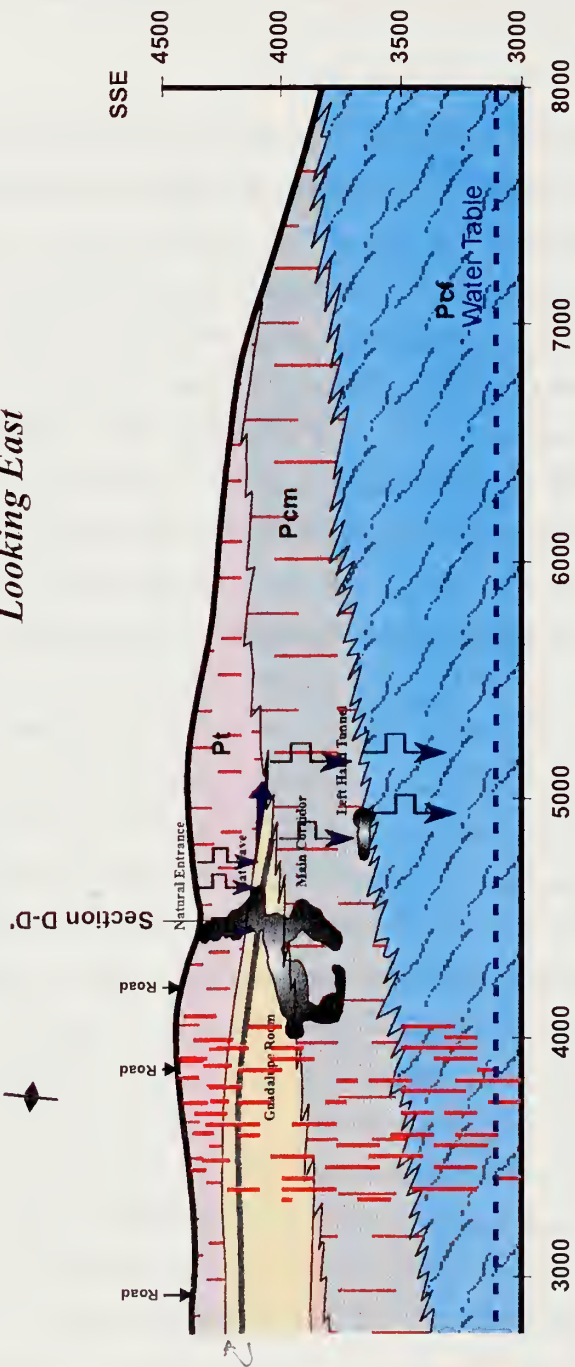
Figure 26. Hypothesized aluminum pathways for Carlsbad Cavern (from Brooke, 1996).

associated with parking lot and maintenance yard runoff and sewer lines leaks in close proximity to the subsurface sampling points (Brooke, 1996). Initial field survey by the authors revealed that the parking lots and maintenance yard discharge their water directly into Bat Cave Draw where it mixes with water from other areas in the Bat Cave Draw drainage. Here, a significant part of the water infiltrates into a microfracture network of the Tansill hydrogeologic unit and percolates downwards until it reaches the Yates Siltstone where it moves laterally down dip to the southeast and east (Brooke, 1996) (Figure 27). From the Yates Siltstone unit, the water may enter the Big Room or Lower Cave area through a microfracture network within the Yates Dolomite and Siltstone hydrogeologic units and the underlying Massive Capitan Limestone, or may move on until it encounters the backreef-reef facies contact where it moves downwards through the Massive Capitan Limestone into the caves below. Brooke (1996) suggested that the zinc concentrations in the Quintessential Right may result from water entering the Massive Capitan Limestone from the backreef-reef transition where the Yates Siltstone hydrogeologic unit pinches out. Although Brooke (1996) suggested that the same process may be responsible for the elevated zinc concentrations in the vicinity of the Crystal Springs Dome area, a direct relationship with a surface source is less obvious (Figure 16).

TOC has been detected in samples taken within the New Mexico Room fracture set area and in cavern passages further to the west, as well as in the Main Corridor, Left Hand Tunnel, and the Quintessential Right (Brooke, 1996). Sources of TOC within the study area include: 1) surface runoff from the parking lots, roads and maintenance yard; 2) bat guano in Bat Cave, and 3) sewer line leaks. Brooke (1996) concluded that potential pathways for TOC in the western sections of Carlsbad Cavern are similar to those for aluminum and zinc. Sources of TOC within the vicinity of the Natural Entrance are the sewer line and the bat and swallow guano. Figure 28 shows water moving from the Natural Entrance area from either the lower parking lot or from the sewer line into the Tansill hydrogeologic unit, where it moves vertically and laterally between the Tansill dolomite and siltstone members until it encounters either the Main Corridor of the cave or the Yates Siltstone unit. Here, the water moves laterally down dip until it is intercepted by the Main Corridor (a local gap in the Yates Siltstone), or if its is too far south of the cave, it either is intercepted by a local microfracture network, or encounters the Yates-backreef-reef facies contact. From here, again, water enters into the fractures of

Bat Cave Draw

Looking East



Description of Map Units

- Pt** Permian Tansill Dolomite and Siltstone - thinly bedded with discontinuous vertical joints of 2 to 8 foot spacing interbedded with laterally discontinuous siltstone 1 to 3 feet thick
- Pcm** Permian Yates Sandstone and Dolomite - sandstones and siltstones compose 1/3 to 2/3 of unit. Dolomite is competent and thinly bedded
- Pys** Permian Yates Siltstone - bed of fine grained quartz and detrital fragments
- Psv** Permian Seven Rivers Dolomite - thinly bedded dolomite
- Pml** Permian Massive Capitan Limestone - reef limestone with continuous vertical joints on spacing of 25 to 100 feet
- Pst** Permian Foreslope Capitan Limestone - beds dipping up to 35 degrees to the southeast

Description of Map Symbols

- CONTACT** (zigzag line)
- SYNCLINE** (line with arrows pointing inward)
- ANTICLINE** (line with arrows pointing outward)
- MACRO-FRACTURE** (thick red line)
- LATERAL FLOW** (blue arrow pointing right)
- VERTICAL FLOW** (blue arrow pointing up)

Figure 28. Hypothesized TOC pathways for Carlsbad Cavern (from Brooke, 1996).

the Massive Capitan Limestone and moves downwards until it intersects the cavern below or enters the Foreslope Capitan Limestone. Brooke (1996) hypothesized that the latter pathway is responsible for the elevated TOC levels in Left Hand Tunnel and Quintessential Right.

Elevated nitrate levels (>36 mg/l) are found almost exclusively within the eastern half of the caverns from just west of the Natural Entrance to the eastern edge of the known caves. In general, these nitrate concentrations increase in concentration to the east. As mentioned before the major sources for nitrate within these parts of Carlsbad Cavern are the bat guano in Bat Cave and a local section of the sewer line. There are four areas with significant nitrate concentrations (Figure 18): 1) near the Natural Entrance, 2) in portions of Left Hand Tunnel parallel to Bat Cave Draw just south of the sewer line, 3) the Lake of the Clouds area, and 4) Quintessential Right. Brooke (1996) hypothesized that nitrate more easily enters the vadose hydrologic system from the sewer line because it is already mixed with water and thus mobile. Nitrate in the guano deposits in the Bat Cave would require a source of water to dissolve and migrate into lower caverns; however, it has been reported by National Park Service personnel and cavers that there are almost no drips or pools in that area to serve as a water source (Brooke, 1996). The only potential source of dissolved nitrate would be bat urine. Again, the migration of this compound is highly influenced by the Yates Siltstone hydrogeologic unit in the same fashion as aluminum and zinc (Figure 29). Because of the location of its sources, the nitrate-enriched water enters either the Left Hand Tunnel area through a microfracture network within the Yates hydrogeologic units followed by migration through the macrofracture network of the Massive Capitan Limestone, or encounters the backreef-reef facies transition where the Yates Siltstone pinches out and the water percolates downwards into the Quintessential Right portion of the cavern. Assuming the presence of the Yates Siltstone above Troll Town, the Bell Cord Room and the Lake of the Clouds, Brooke (1996) considered the higher nitrate levels observed in these cave sections to result from pathways through connected Yates microfracture and Capitan macrofracture networks. Finally, he concluded that the elevated nitrate levels in the New Section just below the Natural Entrance most likely result from runoff entering the Natural Entrance and migrating through the backreef microfracture network.

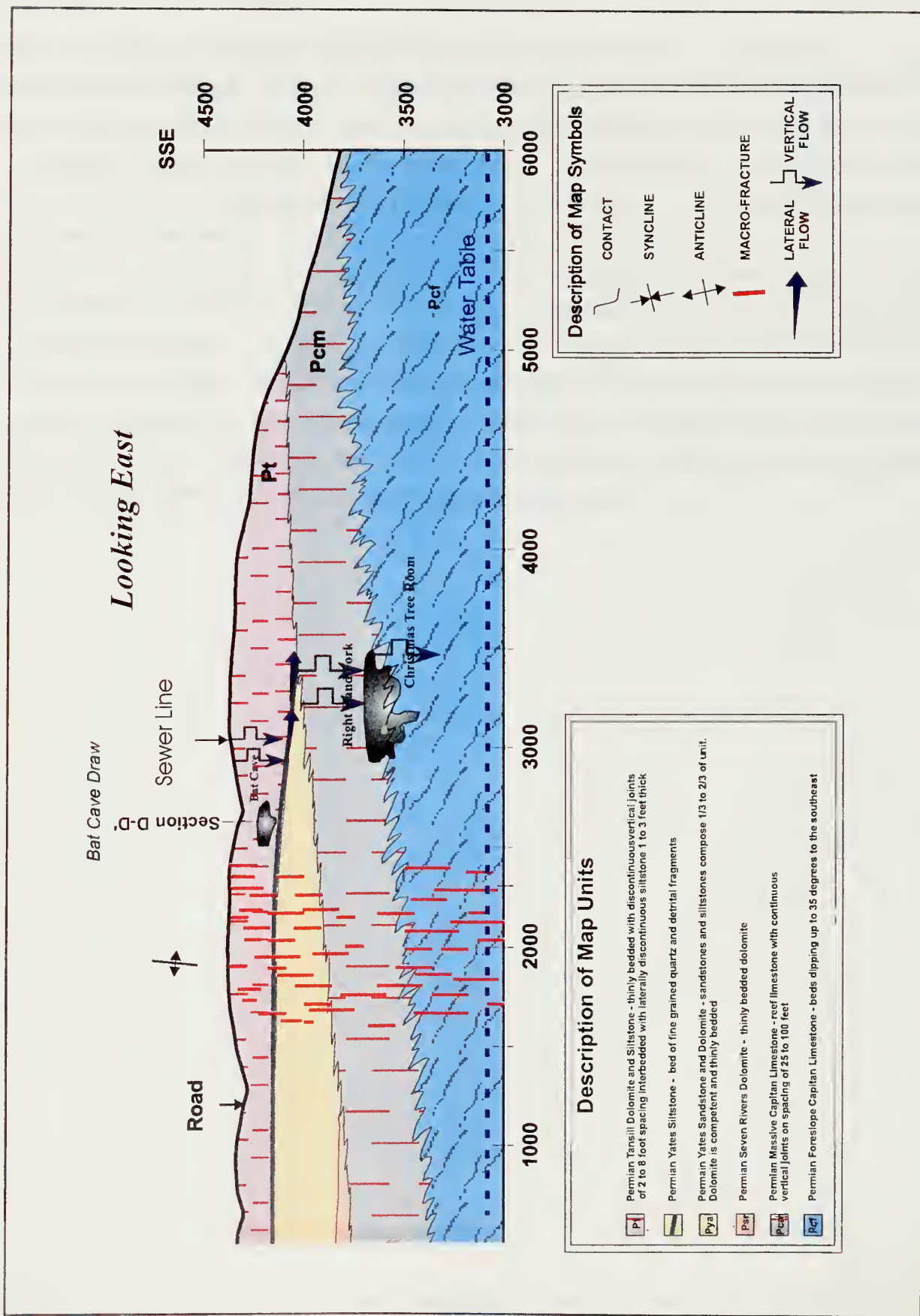


Figure 29. Hypothesized nitrate pathways for Carlsbad Cavern (from Brooke, 1996).

From the discussion above it is evident that these four chemical species act as pathway tracers due to the existence of rather unique sources and the presence of characteristic distributions within the cavern. The spatial connection between sources and observations of individual chemical species can be determined using hydrogeologic framework analysis. The evaluation of possible pathways between surface source and subsurface distributions of selected chemical species, as performed by Brooke (1996), shows that each pathway consists of a combination of vadose flow mechanisms. It demonstrates the importance of delineating the hydrologic system domains using a modified version of the method of Kolm (1993) and Kolm et al. (1996). Furthermore, the chemical pathway analysis identified some likely sources of major anthropogenic changes in cave water quality, specifically runoff from parking lots and maintenance yard, and sewer line leaks. It also showed that the nature of the hydrologic system domains determines where such anthropogenic influences on cave water quality can be found in the future.

VULNERABILITY ASSESSMENT

The determination of the vulnerability of the Carlsbad Cavern for pollution from the surface has been limited to a qualitative assessment based on systematic characterization and conceptualization of the local hydrologic system. The assessment of risk posed by the current sources and practices, a more quantitative procedure by nature, has not been performed due to the complexity of the unsaturated zone above the caverns, the inaccessibility of the rock for hydrologic testing, and the limited time and funding available for this project.

The systematic characterization and conceptualization of the hydrologic system at the Carlsbad Cavern study site identified a number of factors that contribute to the relative high vulnerability of the caves: 1) the absence of a significant, continuous soil zone in most of the study area; 2) the presence of localized but highly permeable fracture zones; and 3) the presence of well developed karst in most of the relevant profile. Well-developed soils typically provide a barrier against rapid infiltration, chemically reduce concentrations of concern in percolating water, and homogenize the water quality through its rather significant storage capacity. Localized permeable fracture zones and karst solution channels provide preferential pathways for rapid contaminant transport.

Factors that have a moderating influence on cave vulnerability include the arid climate, and the presence in part of the study area of the rather continuous Yates Siltstone and a (shallow) subcutaneous zone. The arid climate is responsible for the small amounts of water that infiltrates in the Cavern, providing only a minor driving force for movement of contaminants. Most of the downward flow takes place as a result of intense summer storms when surface water collects at topographic lows and partially infiltrates into the subsurface. However, due to the relative low frequency of such storms, their highly localized presence, and the high evapotranspiration rates in the summer, the cumulative effect of such storms on the downward movement of contaminants is limited. Furthermore, intense homogenization of water quality takes place in most of the study area due to the presence of the subcutaneous zone, the Yates Siltstone, and other low-permeability barriers to rapid infiltration. Over time, this results in a reduction of the chemical concentrations that eventually move downwards beneath these barrier layers. Exceptions

to this damping and diluting mechanism can be found in the “gap” in the Yates Siltstone in the Main Corridor (hydrologic system domain 3), the transmissive macrofractures in hydrologic system domain 2 (Chocolate High, New Mexico Room, Scenic Rooms, Big Room), and the southern edge of the Yates Siltstone at the boundary of domains 1 and 4 (Figure 27).

A major concern is that most of the Park facilities at the surface are situated directly above important cave resources. Many of these facilities are potential sources of contamination. Table 4 lists the various potential contamination sources at the surface, possible pathways from these sources into the cavern, and the areas within the caves most likely to be the recipient of this contamination. This table also include a qualitative assessment of the vulnerability of the recipient cavern areas for pollution from particular sources and events. The conclusions with respect to the recipient Cavern areas and their vulnerability follow directly from the hydrologic system analysis and the subsequent definition of hydrologic system domains described by Brooke (1996), and are corroborated by his chemical sampling results. From Table 4 it is evident that the most threatened areas in Carlsbad Cavern are: 1) Quintessential Right, 2) Left Hand Tunnel, 3) New Section, 4) the Main Corridor between Devil's Spring and Iceberg Rock, and 5) locations in Chocolate High, the New Mexico Room, the Scenic Rooms, and the Big Room area.

Thus far, only limited anthropogenic effects, due to contamination introduced at the surface, have been observed in the caves. Most of the unnatural high concentrations of aluminum, zinc, TOC and nitrate reported by Brooke (1996) can be related to chronic, relatively low-level releases at specific locations at the surface. Although the contaminants found in drips and pools may have significant repercussions for the cavern's ecological system, they pose a very small risk to human beings working in or visiting the caves due to their relatively low concentrations, the small flow rates involved, and the relative inaccessibility of most of the exposure locations.

A variety of accident, spill and leakage scenarios can threaten the water quality in the cavern, and even public health. Major potential sources identified in this study are: 1) leaks in the sewer lines; 2) spills and vehicle fires with subsequent contaminated runoff from the public parking lots and road segments in the western part of the study area; and

Table 4. Pathways and potential exposure locations for contamination.

| Source | Domains | Infiltration Zones | Pathways | Recipient Cavern Area | Vulnerability |
|---------------------------------------------|---------|-----------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------|
| RV/bus parking lot west of visitor's center | 1 and 2 | Diffused and focused infiltration | <p>A. Parking lot runoff towards Bat Cave Draw in domain 1 infiltrates into the Tansill, followed by lateral down-dip flow at the Yates Siltstone towards the facies change at the boundary with domain 4; some localized vertical percolation possible through the Yates.</p> <p>B. Infiltration through parking lot cracks in domain 2 percolates vertically through macrofractures to the caves.</p> | <p>A. Quintessential Right</p> <p>B. Crystal Springs Dome area of Big Room</p> | <p>A. High</p> <p>B. Moderate</p> |
| Car parking lot east of visitor's center | 1 | Diffused and focused infiltration | <p>A. Parking lot runoff towards Bat Cave Draw in domain 1 infiltrates into the Tansill, followed by lateral down-dip flow at the Yates Siltstone to the facies change at the boundary with domain 4; some localized vertical percolation possible through the Yates.</p> <p>B. Infiltration through parking lot cracks in domain 1 percolates vertically through the Tansill, followed by lateral down-dip flow at the Yates Siltstone to the facies change at the boundary with domain 4.</p> | <p>A. Quintessential Right</p> <p>B. Unmapped cavern area between Big Room and Quintessential Right; probably percolates straight to regional water table.</p> | <p>A. High</p> <p>B. Moderate</p> |
| Visitor's center | 1 | Focused infiltration | <p>A. Rain water runoff towards Bat Cave Draw in domain 1 infiltrates into the Tansill, followed by lateral down-dip flow at the Yates Siltstone to the facies change at the boundary with domain 4; some localized vertical percolation is possible through the Yates.</p> <p>B. Fluids from leaks/spills in buildings may seep through cracks in the foundation into domain 1 and percolate through the Tansill, followed by lateral flow at the Yates Siltstone to facies change at the boundary with domain 4; they may also seep directly into the elevator shafts.</p> | <p>A. Quintessential Right</p> <p>B. Unmapped cavern area between Big Room and Quintessential Right, or collects (infiltrates?) At the bottom of the shaft(s).</p> | <p>A. Moderate</p> <p>B. Low</p> |
| Underground lunchroom | 1 | Focused infiltration | Leaks/spills will infiltrate and percolate to the Lower Cave and ultimately to the water table. | Lower Cave | Low |
| Park offices | 3 | Focused infiltration | Fluids from leaks/spills infiltrate into the Tansill and move vertically through the Yates into the Main Corridor because of the localized absence of the Yates Siltstone. | Main Corridor between Devil's Spring and Iceberg Rock | High |
| Employee housing | 1 | Diffuse infiltration | Precipitation infiltrates locally, as do fluids from leaks/spills, and percolates through the Tansill, followed by lateral flow at the Yates Siltstone to domain 3, or to microfracture zones near the anticline axis with downward percolation through the Yates. | Main Corridor between Devil's Spring and Iceberg Rock; Guadalupe Room, Left Hand Tunnel, and New Section | Low |

| Source | Domains | Infiltration Zones | Pathways | Recipient Cavern Area | Vulnerability |
|-----------------------------------|---------|----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------|
| Maintenance yard | 1 | Diffuse infiltration | <p>A. Surface runoff from the yard is mainly towards Bat Cave Draw. Most of the runoff infiltrates in the area between the yard and the bottom of the draw. Excess runoff may reach the draw itself. After infiltrating into the subsurface, it percolates through the Tansill, followed by lateral flow at the Yates Siltstone till it meets microfracture zones near the anticline axis or the facies contact at the boundary with domain 4, where it percolates downwards through the Yates.</p> <p>B. Fluids from leaks/spills infiltrate through cracks or directly from storage tanks and percolate through the Tansill, followed by lateral down-dip flow at the Yates Siltstone till they meet microfracture zones near the anticline axis, where they percolate downwards through the Yates.</p> <p>C. Some rapid surface runoff during intense storms may enter the Natural Entrance where it rapidly infiltrates into the cavern floor and percolates downwards.</p> | <p>A. Left Hand Tunnel and New Section; Quintessential Right</p> <p>B. Left Hand Tunnel and New Section</p> <p>C. Natural Entrance</p> | <p>A. High</p> <p>B. High</p> <p>C. Moderate</p> |
| Bat Cave Draw (lower) parking lot | 3 | Focused infiltration | <p>A. Runoff towards Bat Cave Draw infiltrates into and percolates through the Tansill, followed by lateral down-dip flow at the Yates Siltstone till it meets microfracture zones near the anticline axis or the facies contact at the boundary with domain 4, where it percolates downwards through the Yates.</p> <p>B. Infiltration through cracks directly into the Tansill, followed directly by vertical percolation through the Yates into the Main Corridor because of the localized absence of the Yates Siltstone.</p> | <p>A. Left Hand Tunnel and New Section; Quintessential Right</p> <p>B. Main Corridor between Devil's Spring and Iceberg Rock</p> | <p>A. Moderate</p> <p>B. Extreme</p> |
| Pumphouse | 3 | Focused infiltration | <p>A. Fluids from leaks infiltrates through cracks in the foundation directly into the Tansill and probably moves vertically through the Yates into the Main Corridor because of the localized absence of the Yates Siltstone.</p> <p>B. May percolate through the Tansill, followed by lateral down-dip flow at the Yates Siltstone till it meets microfracture zones near the anticline axis or the facies contact near the boundary with domain 4, where it percolates downwards through the Yates.</p> | <p>A. Main Corridor between Devil's Spring and Iceberg Rock</p> <p>B. Left Hand Tunnel and New Section; Quintessential Right</p> | <p>A. Extreme</p> <p>B. Low</p> |

| Source | Domains | Infiltration Zones | Pathways | Recipient Cavern Area | Vulnerability |
|-------------------------------------------------------------------------------------|----------|-----------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------|
| Main road between service road to maintenance yard and road to lower parking lot | 1 and 2 | Diffuse infiltration | <p>Precipitation infiltrates locally, as do fluids from leaks/spills, and percolates vertically through the Tansill, followed by:</p> <p>A. lateral flow eastward at the Yates Siltstone to domain 2 where it percolates through macrofractures into the cave;</p> <p>B. lateral flow eastward at the Yates Siltstone to domain 3 where it breaks through the Yates in the absence of the Yates Siltstone; or</p> <p>C. lateral flow eastward at the Yates Siltstone till it meets microfracture zones near the anticline axis, where it percolates downwards through the Yates.</p> | <p>A. Chocolate High and Scenic Rooms area</p> <p>B. Main Corridor between Devil's Spring and Iceberg Rock</p> <p>C. Left Hand Tunnel and New Section</p> | <p>A. Moderate</p> <p>B. Low</p> <p>C. Low</p> |
| Main road between road to lower parking lot and visitor's center parking lots | 1 | Focused infiltration | Runoff towards Bat Cave Draw in domain 1 infiltrates into the Tansill, followed by lateral down-dip flow at the Yates Siltstone towards domain 2 where most of it percolates vertically through the macrofractures. Some excess runoff may infiltrate further downstream in Bat Cave Draw. | Scenic Rooms, Boneyard, and Hall of Giants part of the Big Room | Moderate |
| Road between main road and lower parking lot | 2 | Focused infiltration | Runoff towards Bat Cave Draw in domain 2, where most of it percolates vertically through the macrofractures. Some excess runoff may infiltrate further downstream in Bat Cave Draw. | New Mexico Room and Scenic Rooms | High |
| Service road near offices | 3 | Focused infiltration | Water and fluids from leaks/spills infiltrate into the Tansill and move vertically through the Yates into the Main Corridor because of the localized absence of the Yates Siltstone. | Main Corridor between Devil's Spring and Iceberg Rock | High |
| Main road north of maintenance yard and service road to maintenance yard | 1 | Diffuse infiltration | Water and fluids from leaks/spills infiltrate locally and percolate through the Tansill, followed by lateral down-dip flow at the Yates Siltstone till they meet microfracture zones near the anticline axis, where they percolate downwards through the Yates, or towards the contact at Walnut Canyon. | Seeps along seep line in Walnut Canyon | Low |
| Sewer line from housing, offices and maintenance yard to pumphouse | mostly 3 | Focused infiltration | Fluids from leaks/spills infiltrate into the Tansill and move vertically through the Yates into the Main Corridor because of the localized absence of the Yates Siltstone. | Main Corridor between Devil's Spring and Iceberg Rock | High |
| Sewer line from pumphouse and visitor's center to turn south for crossing ridge top | 1 | Focused infiltration | Surface runoff towards Bat Cave Draw; sewage infiltrates into the Tansill, followed by lateral down-dip flow at the Yates Siltstone to the facies change at the boundary with domain 4; some localized vertical percolation possible through the Yates. | Left Hand Tunnel, Quintessential Right | High |
| Sewer line from Bat Cave Draw to Delaware Basin | 4 | Diffuse infiltration and rapid surface runoff | Some surface runoff towards Bat Cave Draw, mostly local infiltration; sewage infiltrates into the Tansill, followed by lateral down-dip flow at the Yates Siltstone to the facies change at the boundary with domain 4; some localized vertical percolation possible through the Yates. | Quintessential Right, Lake of the Clouds area | Moderate |

3) spills, leaking tanks, fires and other accidental releases from the maintenance yard. Especially, accidents whereby a significant amount of contaminating fluid (water, gasoline) is released, or that happen just before or during intense rain storms, may pose elevated risks for the caves. After such a fluid has infiltrated in the rock, little can be done to remove or neutralize the contaminant. Often, the contaminant may be in the vadose zone for years before any change in cave water quality may be noticed. Flushing by adding water to the area where the contaminant has entered the soil may make the situation even worse, as it will prevent the system from its natural capability to reduce chemical concentrations through mixing (homogenization), volatilization, and contaminant degradation. To protect the caves from contamination from the surface, the chance of a significant release at the surface needs to be reduced through management policies, accident mitigation procedures, and engineering measures.

The major problem with respect to the maintenance yard and the three public parking lots is the direction of the surface runoff. In all four areas, the paved surfaces drain towards the most sensitive part of the system: Bat Cave Draw. These surfaces are subject to a number of threats such as chronic release of metals oil, and other compounds from vehicles, incidental releases of various chemicals from accidental spills (e.g., when filling storage tanks), and short-term releases from vehicle accidents or fires and the fluids used to mitigate these incidents. Rerouting the drainage from these areas away from Bat Cave Draw should significantly reduce the risk for cave contamination. This might be a rather straightforward engineering problem for the parking lots near the visitor's center and for the maintenance yard, either through regrading the paved surface to let them drain off towards the Delaware Basin or Walnut Canyon, respectively, or by the construction of collection drains which are rerouted to the aforementioned discharge areas. It is most likely not (financially) feasible for the lower parking lot (near the Natural Entrance) due to its topographic position. Here, only deeply buried gravity drains or pumped drainage can reroute parking lot runoff to safe areas. Closing this area for regular vehicle access may be the only solution. Obviously, removing all vehicles, contaminant storage devices and potentially contaminating sources from the maintenance yard and its surroundings significantly reduces the risks to the caves.

In addition to the runoff problem, the paved surfaces of the parking lots and the

maintenance yard may have cracks that provide an easy path for contaminants into the underground. Regular maintenance of these paved surfaces would reduce the risk of contamination of the cavern through direct infiltration from these areas. Furthermore, the presence of the paved surfaces may have prevented infiltration of rain water in the past, keeping fluids that may have leaked from storage tanks underneath these surfaces, relatively in place (no flushing), giving nature time to (aerobically) degrade these fluids. To determine if any leaks have taken place from these storage tanks, soil sampling and soil water and soil gas monitoring may be called for. Such soil monitoring is also good practice for other above- and underground storage tanks at the Park. The best practice is to eventually remove all fluid storage devices from the Cavern area.

It should be noted that all accident mitigation procedures (fire fighting, spill removal) should use as little water as possible, and try to avoid flushing contaminants straight to existing drains or the side of the paved areas where they rapidly infiltrate in the rock. Special measures should be taken to remove as much of the spilled materials off-site instead. Also, vehicle firefighting procedures should be aimed at releasing minimal fluids and contaminants to the soil.

Another major problem area is the sewer line complex. The study has given strong indications that water quality in certain areas of the cavern has been affected by leaks and spills from the sewage system. Areas mostly affected, or most likely to be affected by this source are the Main Corridor (domain 3), Left Hand Tunnel (domain 1) and Quintessential Right (boundary between domain 1 and domain 4). Sewage seepage into the underground is a combination of chronic leaking of the sewer lines and incidental releases from clogging and subsequent overflow of manholes. Effective mitigation requires regular preventive inspection and maintenance of the lines (removal of clogging materials, visual and video inspection, checking for leaks) and an engineering study for improvements (replacement with sealed, high capacity lines to be installed under gradients for maximum through flow, and removal of constriction points, etc.). Another option is rerouting the sewer line from the visitor's center directly towards the Delaware Basin, and rerouting the sewer lines from offices, housing and maintenance yard east to a point past the farthest known cave area (Lake of the Clouds), and from there south to the Delaware Basin.

One of the most important “worst-case” scenarios may be an accident occurring during filling of a fuel storage tank. If such an accident causes a fire, a significant spill may result that can not immediately be cleaned up due to the explosion hazard as long as the fire has not been extinguished. If the spill happens near the visitor’s center or at the maintenance yard, a significant, hard-to-mitigate contamination of the subsurface may result. Continuing this worst-case scenario, the contaminant may find a rapid pathway towards exposed caves in hydrologic system domain 2 or 3 resulting in fuel dripping from cave ceilings. In the cave environment, such concentration of volatile contaminants, together with the oxygen in the air may result in an explosive mixture, posing a hazard to visitors and staff, as well as to the cave resources and its ecosystem. Furthermore, such an incident may be accompanied by a strong fuel smell in the caves. Another scenario of concern is the massive failure or frequent occurrence of selected failure of the sewer system, resulting in the buildup of chemical and pathogenic contaminants in related areas of the Cavern. Although the resulting contamination may not affect the physical cave environment, it can pose a major risk for humans and the cave ecosystem.

All of the drip areas in the cave have relatively moderate to high risk with respect to contamination from the surface. Most of the dry sections of the cavern are also rated as having a low risk for contamination from the surface. It should be noted that the Oak Spring area is relatively safe from contamination as it collects most of its water from areas north of the surface infrastructure. It is hypothesized that Oak Spring receives its water primarily from the area west of the main road. This water flows down dip along the Yates Siltstone towards domain 2, where it collects the combination of horizontally extended macrofractures and the Yates Siltstone channels it north-northwest towards the spring. A slight dip of the formation towards Walnut Canyon north of the anticline axis may exacerbate this mechanism. Only the segment of the main road near the side road to the lower parking lot may be a source of pollution of Oak Spring.

Table 5 lists various observed problem areas, together with the recipient Cavern area, the risk of exposure of humans or the ecosystem, and selected preventive and mitigative solutions. Most of the measures discussed are preventive in nature. Mitigation measures are limited to post-incident activities to be performed at the surface. Due to the nature of the hydrologic system of Carlsbad cavern, very few measures can be taken to mitigate

contamination between the ground surface and the open caves. If significant contamination breakthrough occurs in the caves, mitigation should focus on capturing the contamination directly from the drips, or removing it as soon as possible from floors and pools, in a manner that prevents further spreading the contamination to other parts of the caves. Table 5 is not all-inclusive. Details of particular preventive actions need to be studied further, particularly by Park management, in close consultation with Park maintenance staff and outside engineering experts. Also, for a number of potential problems, more than one measure has been listed. Some of these measures are alternatives, others can be implemented in conjunction with each other. It should be noted that this study has been aimed at providing the scientific basis for measures to be taken to protect the caves, not at developing alternative management policies or designing engineered solutions.

Table 5. Sources, potential contamination problems, and prevention or mitigation measures.

| Source | Potential Problems | Recipient Cavern Area | Risk of Exposure | Prevention or Mitigation Alternatives |
|---------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| RV/bus parking lot west of visitor's center | <ol style="list-style-type: none"> chronic release of metals, oil, etc. from cars car fire/crash with spill | <ol style="list-style-type: none"> Crystal Springs Dome area of Big Room Quintessential Right | <ol style="list-style-type: none"> Moderate High Moderate High | <ol style="list-style-type: none"> close parking lot to traffic (prevention) ensure that the surface is sealed and no open cracks exist (prevention) ensure rain water is routed to south side of parking lot (prevention) ensure that water used to clean up is routed to south side of parking lot (mitigation) |
| Car parking lot east of visitor's center | <ol style="list-style-type: none"> chronic release of metals, oil, etc. from cars car fire/crash with spill | <ol style="list-style-type: none"> unmapped cavern area between Big Room and Quintessential Right; probably percolates straight to regional water table. Quintessential Right | <ol style="list-style-type: none"> Moderate High Low Low | <ol style="list-style-type: none"> close parking lot to traffic (prevention) ensure that the surface is sealed and no open cracks exist (prevention) ensure rain water is routed to south side of parking lot (prevention) ensure that water used to clean up is routed to south side of parking lot (mitigation) |
| Visitor's center | <ol style="list-style-type: none"> utility line breaks (utility shaft) storage tank leak (chronic) or spill (while filling) sewage problems (restrooms, lines) | <ol style="list-style-type: none"> Quintessential Right unmapped cavern area between Big Room and Quintessential Right, or collects (infiltrates?) At the bottom of the shaft(s). | <ol style="list-style-type: none"> Moderate High High Low Low Low | <ol style="list-style-type: none"> regular inspection of utility lines (prevention) ensure that bottom of utility shaft is sealed high enough to capture any spill (prevention) use latest technologies replacing storage tank and related lines (prevention) sample soil around storage tank to determine if leaks are present (detection) |
| Underground lunchroom | <ol style="list-style-type: none"> utility line breaks (utility shaft) sewage problems (pump room, restrooms) | <ol style="list-style-type: none"> Lunchroom Left Hand Tunnel Big Room | <ol style="list-style-type: none"> Moderate Moderate Low Low | <ol style="list-style-type: none"> move lunch facilities and shops above ground (prevention) perform engineering evaluation of restroom/sewer facilities with respect to risk (prevention) |
| Park offices | <ol style="list-style-type: none"> sewage problems | <ol style="list-style-type: none"> Main Corridor between Devil's Spring and Iceberg Rock | <ol style="list-style-type: none"> High | <ol style="list-style-type: none"> inspect and improve sewer lines (prevention) remove offices from above the caves to distant area (prevention) |

| Source | Potential Problems | Recipient Cavern Area | Risk of Exposure | Prevention or Mitigation Alternatives |
|-----------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Employee housing | <ol style="list-style-type: none"> 1. sewage problems 2. lawn maintenance 3. buried tank leaks (chronic) or spill (while filling) | <ol style="list-style-type: none"> A. Main Corridor between Devil's Spring and Iceberg Rock B. Guadalupe Room and New Section C. Left Hand Tunnel | <p>A1, B1, C1: Moderate A2, B2, C2: Moderate A3, B3, C3: Low</p> | <ol style="list-style-type: none"> 1. inspect and improve sewer lines (prevention) 2. abandon use of lawn chemicals (prevention) 3. perform regular inspection of storage tanks (detection) 4. remove offices from above the caves to distant area (prevention) |
| Maintenance yard | <ol style="list-style-type: none"> 1. chronic release of metals, oil, etc. from vehicles rain, car washing, maintenance) 2. car fire/crash with spill 3. sewage problems 4. buried tank leaks (chronic) or spill (while filling) 5. leaks from stored materials in backyard | <ol style="list-style-type: none"> A. New Section B. Left Hand Tunnel and Quintessential Right C. Natural Entrance | <p>A1-5. High B1-5. High C1-5. Moderate</p> | <ol style="list-style-type: none"> 1. close maintenance yard (prevention) 2. ensure that the surface is sealed and no open cracks exist (prevention) 3. ensure rain water is routed to north side far enough away from Bat cave Draw not to pose a danger for the caves (prevention) 4. ensure that water used to clean up is routed to same way as under 3. (mitigation) 5. perform soil sampling near underground tanks and unsurfaced storage areas to determine if leaks are present (detection) 6. remove underground storage tank(s) and related pipe lines (prevention/mitigation?) 7. remove all potentially leaking materials from storage area east of maintenance yard (prevention/mitigation?) 8. ensure that paint materials in and around paint shop can not leak into the ground; add hard surface area around paint shop (prevention) |
| Bat Cave Draw (lower) parking lot | <ol style="list-style-type: none"> 1. chronic release of metals, oil, etc. from cars 2. car fire/crash with spill | <ol style="list-style-type: none"> A. Main Corridor between Devil's Spring and Iceberg Rock B. Left Hand Tunnel and Quintessential Right C. New Section | <p>A1. High A2. Extreme B1. Moderate B2. High C. Low</p> | <ol style="list-style-type: none"> 1. close parking lot to traffic (prevention) 2. ensure that the surface is sealed and no open cracks exist (prevention) 3. mitigate accidents/spills with little water while closing drains to Bat Cave Draw (mitigation) |
| Pumphouse | <ol style="list-style-type: none"> 1. sewage overflow, line leaks | <ol style="list-style-type: none"> A. Main Corridor between Devil's Spring and Iceberg Rock B. Left Hand Tunnel and Quintessential Right C. New Section | <p>A1. High B1. Moderate C1. Low</p> | <ol style="list-style-type: none"> 1. perform regular inspection and maintenance (prevention) 2. perform engineering study of sewage system to assess problems and design improvements (prevention/mitigation) |

| Source | Potential Problems | Recipient Cavern Area | Risk of Exposure | Prevention or Mitigation Alternatives |
|----------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Main road between service road to maintenance yard and road to lower parking lot | <ol style="list-style-type: none"> 1. chronic release of metals, oil, etc. from cars 2. car fire/crash with spill | <ol style="list-style-type: none"> A. Chocolate High and Scenic Rooms area B. Main Corridor between Devil's Spring and Iceberg Rock C. Left Hand Tunnel and New Section | <ol style="list-style-type: none"> A1-2. Moderate B1-2. Low C1-2. Low | <ol style="list-style-type: none"> 1. close road to visitors (prevention) 2. ensure safety on road (bright road lines, low speeds; prevention) 3. enact water-poor accident mitigation procedures (prevention) |
| Main road between road to lower parking lot and visitor's center parking lots | <ol style="list-style-type: none"> 1. chronic release of metals, oil, etc. from cars 2. car fire/crash with spill | <ol style="list-style-type: none"> A. Scenic Rooms, Boneyard, and Hall of Giants part of the Big Room | A1-2. Moderate | <ol style="list-style-type: none"> 1. close road to visitors (prevention) 2. ensure safety on road (bright road lines, low speeds; prevention) 3. enact water-poor accident mitigation procedures (prevention) |
| Road between main road and lower parking lot | <ol style="list-style-type: none"> 1. chronic release of metals, oil, etc. from cars 2. car fire/crash with spill | <ol style="list-style-type: none"> A. New Mexico Room and Scenic Rooms | A1-2. High | <ol style="list-style-type: none"> 1. close road to visitors (prevention) 2. ensure safety on road (bright road lines, low speeds; prevention) 3. enact water-poor accident mitigation procedures (prevention) |
| Service road near offices | <ol style="list-style-type: none"> 1. chronic release of metals, oil, etc. from cars 2. car fire/crash with spill | <ol style="list-style-type: none"> A. Main Corridor between Devil's Spring and Iceberg Rock | A1-2. High | <ol style="list-style-type: none"> 1. close maintenance yard (prevention) 2. ensure safety on road (low speeds; prevention) 3. enact water-poor accident mitigation procedures (prevention) |
| Main road north of maintenance yard and service road to maintenance yard | <ol style="list-style-type: none"> 1. chronic release of metals, oil, etc. from cars 2. car fire/crash with spill | <ol style="list-style-type: none"> A. seeps along seep line in Walnut Canyon | A1-2. Low | <ol style="list-style-type: none"> 1. close road to visitors (prevention) 2. ensure safety on road (bright road lines, low speeds; prevention) 3. enact water-poor accident mitigation procedures (prevention) |
| Sewer line from housing, offices and maintenance yard to pumphouse | <ol style="list-style-type: none"> 1. sewage overflow, line leaks | <ol style="list-style-type: none"> A. Main Corridor between Devil's Spring and Iceberg Rock | A1. High | <ol style="list-style-type: none"> 1. perform regular inspection and maintenance (prevention) 2. perform engineering study of sewage system to assess problems and design improvements (prevention/mitigation) 3. reroute sewer line (prevention) |

| Source | Potential Problems | Recipient Cavern Area | Risk of Exposure | Prevention or Mitigation Alternatives |
|-------------------------------------------------------------------------------------|--------------------------------|--------------------------------------------------|------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Sewer line from pumphouse and visitor's center to turn south for crossing ridge top | 1. sewage overflow, line leaks | A. Left Hand Tunnel, Quintessential Right | A1. High | <ol style="list-style-type: none"> 1. perform regular inspection and maintenance (prevention) 2. perform engineering study of sewage system to assess problems and design Improvements (prevention/mitigation) 3. reroute sewer line (prevention/mitigation) |
| Sewer line from Bat Cave Draw to Delaware Basin | 1. sewage overflow, line leaks | A. Quintessential Right, Lake of the Clouds area | A1. Moderate | <ol style="list-style-type: none"> 1. perform regular inspection and maintenance (prevention) 2. perform engineering study of sewage system to assess problems and design Improvements (prevention/mitigation) 3. reroute sewer line (prevention/mitigation) |

CONCLUSIONS

The new characterization and conceptualization approach to understand the hydrologic system, taken in this study, together with chemical sampling of cave waters, have proven successful in determining qualitatively the vulnerability of Carlsbad Cavern for contamination from the surface. The integration of geologic, geomorphologic, climate, topographic vegetation and hydrologic information in a single conceptual model has been crucial to determining the major hydrologic elements comprising the hydrologic domains in the study area. These domains, in turn, provided the framework for the analysis of potential pathways from the surface to the caves. An unique aspect of the study is the successful extension of the characterization and conceptualization approach of Kolm (1993) and Kolm et al. (1996). In the past, this approach was primarily applied to humid and arid saturated flow systems. In this study, the method was adapted to cover a combination of an unsaturated flow system and a karst hydrologic system.

Although Carlsbad Cavern is highly vulnerable for contamination from the surface, currently, there are few indications that massive contamination is occurring. Some smaller incidences have been detected, primarily related to the sewer lines and parking lot runoff. However, it is very conceivable that in the future major contamination incidents may take place if no preventive measures are taken.

After a contaminant has entered the subsurface, little can be done to remove it until it arrives, often many years later, in an exposed cave. There, some measures can be taken to capture and remove the contaminant and to reduce its potential effect on humans and cave ecosystems. Even then, most contamination incidents will be rather localized or will occur in areas not accessible for visitors, allowing most of the caves to be kept open for the public.

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